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CHAMPIONS!

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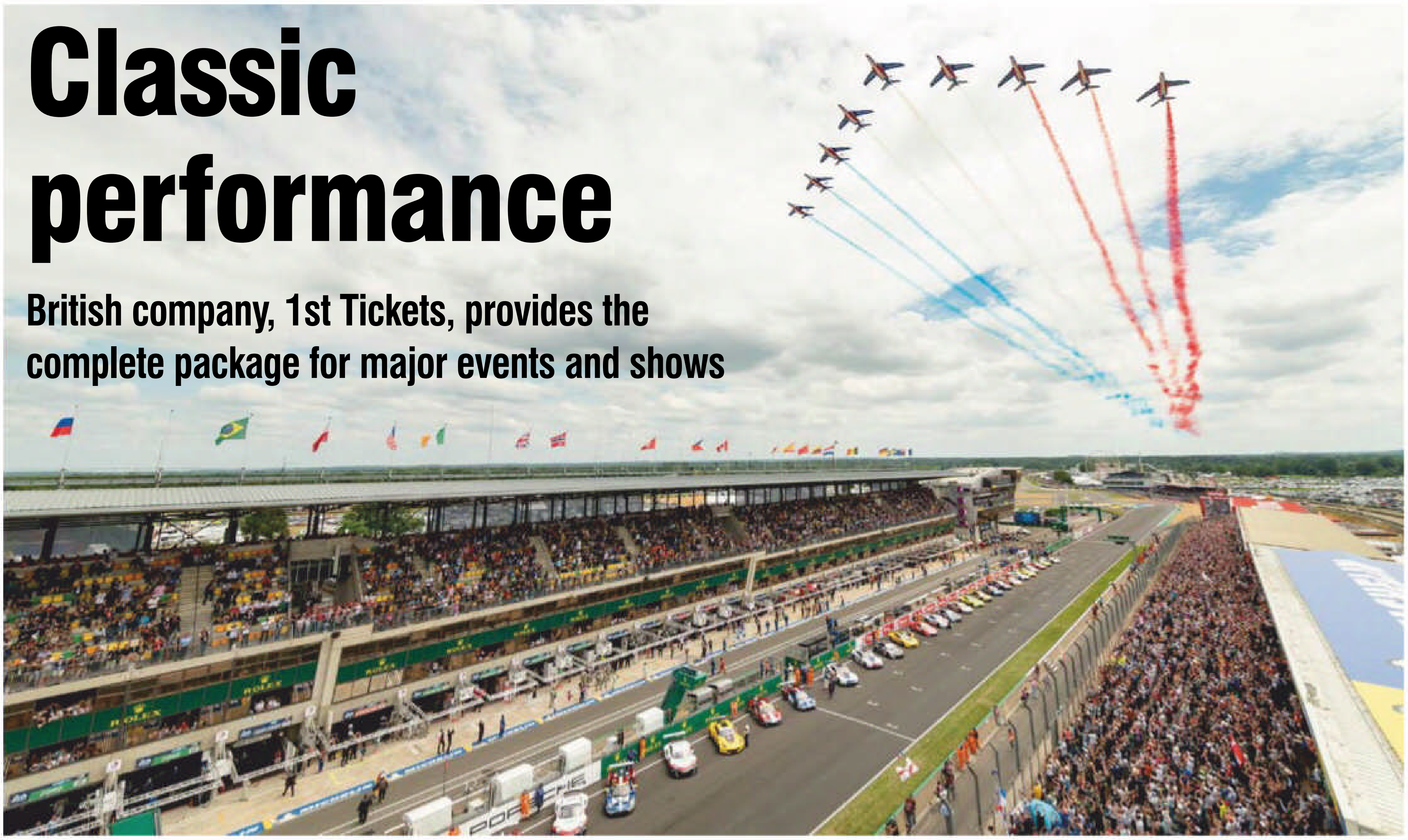
The Macau GT Cup didn't have the international presence to which it has become accustomed but instead returned to its traditional roots for 2020

Classic performance

British company, 1st Tickets, provides the complete package for major events and shows



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Founded in 2007, 1st Tickets is a privately-owned, UK-based, bonded tour operator that specialises in endurance and classic car motorsport events. Since then, we have grown into a well known and respected brand in this market. We are a long-standing official agent for the Automobile Club de l'Ouest, creators and organisers of the 24 Hours of Le Mans, and have well-established relationships with car clubs and motoring brands.

Each year, we help up to 4500 people with their travel and accommodation needs for the 24 Hours of Le Mans, Le Mans Classic (bi-annual event), Spa Classic and Moto 24 Hours. We offer a range of packages to suit all pockets, from simple ticket-only deals to self-drive, private camping packages with tented accommodation and meals included.

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Our campsites are either within the circuit or just a short walk away, with excellent facilities, including a large marquee with dining area, bar, charging points, free Wi-Fi and race coverage. They are secure areas that have a friendly and relaxed atmosphere, where our customers enjoy good company, fine cars and great service.

Photo: Stephanie Bezard

Photo: 1st Tickets Limited

At the Spa Classic, we have a range of accommodation options including camping, self-catering chalets / apartments and three and four-star hotels in the town of Spa and surrounding area. We also have our hospitality suite above the endurance pits, which is an excellent base from which to relax and watch the classic racing.

At both the Le Mans and Spa Classic, we provide display parking within the circuit (where your car becomes part of the event), parade laps and track lap sessions, enabling our customers to drive the circuit in their own qualifying car.

We are specialists in our field, with extensive knowledge about our events, how best to get there, the accommodation options in and around the circuits and the various grandstands and event extras that would complement your package.

Our team have experienced the events first-hand and are able to guide you through all the combinations and options. We pride ourselves in our high level of customer service and retention, with many customers returning year on year.

As well as private bookings, we also offer bespoke corporate packages tailored to suit the client's needs. This can include reserved parking areas, pit and gridwalk access, as well as hospitality areas at the event. In the past, we have worked with various companies and groups, including a major car manufacturer.

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1st Tickets

Pushing the limits

The 2020 season posed unique challenges for race teams competing all over the world

The trucks are now back at base and the racecars won't run in anger again in 2020. Returning home to England feels great after what can only be described as a really odd season of racing in the US.

When the IMSA season restarted after the spring lockdown, the schedule had to be compressed into a much shorter period. What this meant for the teams is nobody had a day off for a long time as it was a case of prepare the cars, travel, race the cars, travel, repeat.

We returned to competition in July, had all of August off, and then finished the season in another two and a half months, so we had a total of just three and a half months of racing (the IMSA season normally spans 10), and that has put our team, and I am sure others, under intense pressure. This has been good in some ways and bad in others.

What is good about that is the time schedule is so condensed you are always on the go. There's never a day you can take off. That's because even though the cars are all built up in the workshop, we're still looking at preparation work, making sure all the systems are working and ensuring the organisational side of everything is done.

It has been odd in that respect because we've never had that level of pressure to get everything done in such a short period of time.

Be prepared

I actually don't think that was a bad thing, though, because it focussed everybody and forced them to be in a location to always be working on the racecar, whether it was writing a run sheet to checking the fitment of parts. Anything that wasn't prepared and in place, or organised the way our competitors would have done, we found out when we went to the tracks, so we had to be precise, efficient and thorough.

If you find anything missing during the race weekend, it's too late to do anything about it, as we found out at Petit Le Mans in October. At every event, I'd say we had something happen that we learnt from. We would then try to do better for the next event, and something else would come up. Dealing with the unforeseen issues in such a compressed timescale was probably the hardest part of it all.

The cost of racing

Logistics play a huge part in racing. A lot of teams are based in Indianapolis, North Carolina or dotted around Florida so, when IMSA arranged the race at Laguna Seca after Petit and before the Sebring 12 hours, it made life a lot harder. I understand why they did it, as WeatherTech is a series sponsor and we have to have a race at their track. As professional race teams, you make it work, there's no two ways about it, but it comes at a cost, both in financial and human terms.

Having that race in California, on the west coast of the US and just about as far from our base in Mooresville as you could get, puts so much pressure on the team, especially when something goes wrong on a car that you need to resolve. An extra day in the workshop would have been beneficial to do that, but that option simply wasn't there.

Just moving the cars across America takes a minimum of two and a half days, possibly even up to four, depending on the weather as they travel through Texas (which delayed our trucks).

Rick Dole, IMSA

The flag has fallen on the 2020 IMSA season with victory for Mazda at Sebring

Accounting for both directions, that's an awful lot of downtime where we are unable to work on the cars, which is not easy to handle when you've got quite an intricate car and a race on the far side of North America slotted between two of the series' blue riband endurance events.

There's a lot of attention to detail required with the DPi cars. They are fundamentally LMP2 cars with a very sophisticated aero kit so, if you get something wrong, you could be chasing it for a long time. It could be with you for two events before you find it's something as simple as the floor not quite being in the right position, but without the right equipment with you at the track to measure, *and* with a compressed timeframe to turn the car around, there just isn't the time to do everything as you normally would.

Winning ways

Looking back on the season, though, it would be easy to say that it was all a bit of a nightmare and wasn't good, but that just wouldn't be right. Despite the extra challenges put upon us, the team won the Sebring 12 Hours.

Racing without the fans for much of the season, however, was a loss felt by all of the teams. The fans add a particular buzz to an event and it was hard not having them there, but we worked as normal to prepare the cars and the racing was good. In terms of television viewers and exposure, it was a great season for the championship as a whole, and I'm sure we've picked up new fans along the way.

Everyone worked hard to overcome the unique challenges in this crazy year. We got to go racing again, we made it work and it was good to be an integral part of that. We got out there and did the thing we love, and that counts for a lot in my book.

Leena Gade is the vehicle dynamics centre manager and race engineer at Multimatic Engineering, UK

We've never had that level of pressure to get everything done in such a short space of time

Continuation or abomination?

The case for and against clones of historic racecars

The revelation that a limited edition 'reproduction' 1958 Vanwall VW5 F1 car is being created by Hall & Hall has been followed by a similar announcement concerning BRM's fabled 1950's Type 15. Jaguar had already pre-empted the dash to cash with its 'continuation' of the Le Mans-winning D-Type sports racer, preceded by XKSS and lightweight E-Type reproductions. There will undoubtedly be more such examples, as current technology means there is virtually no limit now to what can be viably reproduced, given people with deep enough pockets to buy them, of course.

Purists have no doubt thrown up their hands in horror, especially those fortunate enough to own the *pur sang* racers. What effect will there be on the stratospheric values of their prized investments now that just rich – rather than super-rich – folk, whose offshore accounts can stand being dented by a couple of million, can obtain an ostensibly identical car?

Providing these high quality reproductions aren't churned out by the dozen (unlikely, although there will always be the temptation to sell more than the initial run), it won't make a jot of difference. Much is made in the presentation of these new cars of how faithful they are to the team cars of the time. But unique patina and history cannot be replicated, in the same way that even a brilliantly faked Van Gogh is never going to raise the same emotions as one of the Master's originals. To see and touch the real thing is to see and touch history.

Exciting times

My guess is that, with a little thought, the benefits of being able to obtain a replica will outweigh any anxieties, especially in regard to exceptionally rare machines such as the Vanwall and the BRM. I find the commitment to tool up for and manufacture the latter's incredible engine, plus transmission, very exciting. The Vanwall is less complex, but almost comparable.

After all, if somebody has been able to afford multi-millions of pounds for a 'real' car, it makes sense to spend another couple of millions on a cloned car to race, without fear of severely damaging the priceless – and increasingly frail – old beauty, safe in storage for posterity and occasional demonstration only.

Important other upsides are that enthusiasts, young and old, can continue to enjoy the thrill of seeing and hearing glorious historic-era cars live and on track. For example, with just one actual 1950's example in existence, and unable to be raced, how else will anybody ever experience the spine-tingling scream from the BRM's blown, 1.5-litre V16 engine?

The satisfying employment required in making these incredible machines is very valuable too, especially now, and so is passing on traditional skills to trainees, helping ensure such artistry is not lost forever.

Whether or not you agree with recreations, there are fine engineering opportunities present in their design, construction and use

Copies, clones, reproductions, recreations, continuations, call them what you will, it's been happening for donkey's years. How many Maserati 250Fs currently racing are original, I wonder? Attending the annual historic races at Angoulême with my brother a while ago, the driver of one of the dozen or so pretty and nicely aged Type 35B Bugattis lined up commented that only three were in fact genuine!

It's no secret that Audi commissioned Crosthwaite & Gardiner to recreate its 1930s Silver Arrows, though not for sale. C & D-Type Jaguars, Ford GT40s and Lola T70s are being knocked off all over the place, some good, many of dubious quality and faithfulness to the originals. Where this strays into fraud is when they are passed off as the real thing. There has always been a seamy side to historic car dealing.

While sales director at Lola Cars, I was subjected to dodgy requests (always denied!) for chassis plates that had 'gone missing'. In particular, from owners of T70 Mk3s tarted up with the bodywork of the later, considerably more valuable Mk3bs, in order to pull the wool over the eyes of unsuspecting buyers.

Surely, only if there is a proper link to the original manufacturer (the Owen family in the case of the BRM), or to the owner of the naming rights (Vanwall), can the terms 'reproduction' or 'continuation' really be acceptable?

As long as the build accuracy and quality of these cars is open to knowledgeable scrutiny and confirmation, then at least one can be sure of what they are, free of any uncertainties. Therefore, everything else must be considered a replica.

Race relevance

An interesting conundrum strikes me regarding these reproductions. At which point does the claim 'identical to original in every detail' inevitably have to depart? Current mandatory FIA safety regulations to fuel and oil systems for historic cars, amongst other parts, have to be met if these cars are to race. More questionably, and particularly relevant to the BRM. Who would want to build in the unreliability issues that so dogged the cars in their heyday?

Modern materials and tools and the use of CAD / CAM may help, but lessons learned during the time that the V16 has been run, right up to recent years, *must* be being incorporated. Nobody is going to stump up two million quid for a racecar that rarely makes it to the finish line. And it wasn't just the engine. Stirling Moss once said the car was the worst handling device he'd ever driven, with poor brakes and bad steering. While I imagine some of this was improved during the BRM's competition life, there won't be drivers of the calibre of Moss driving these difficult beasts.

Nonetheless, I am looking forward to hearing again the indescribable 12,000rpm shriek of that crazy supercharged racing engine in action, and seeing first hand the distinctive, high-tailed aerodynamics of the Vanwall. Plus who knows what else in years to come?

At which point does the claim 'identical to original in every detail' inevitably have to depart?

2020 saw Mercedes become seven-time constructors' champion and Mercedes driver, Lewis Hamilton, claim his seventh world championship drivers' title. Hamilton's record-breaking number of wins in Formula 1 makes him the most decorated driver of all time

Black Arrows

***Racecar* investigates how Mercedes has stayed ahead of the F1 pack in 2020, and how it intends to continue doing so in 2021**

By STEWART MITCHELL

The 2020 season has been like no other, with the impact of coronavirus shifting the norm in every aspect of life. However, one thing feels like *déjà vu*, and that is Mercedes AMG Petronas Formula 1 team securing the Formula 1 constructors' title, this one making them seven-time world champions.

That's every year since the dawn of the hybrid car regulations in 2014, and the teams' domination seems not to be yielding any time soon. Mercedes' success is not thanks to one constituent part it has above the rest of the grid, it's the combination of all the technology in the car, the drivers and the team's gameplay all working in harmony to create an ostensibly unstoppable force when it counts.

The 2020 Mercedes Formula 1 racecar, the W11 EQ Performance (W11 for short), is built to the 2020 Formula 1 technical regulation set, which features very few changes compared to 2019. However, this didn't stop Mercedes bringing significant developments to the W11 that see it adopt new philosophies in some areas when compared to its predecessor, the W10.

This philosophy shift, and the technical solutions that coincide with it, primarily revolve around central architectural modifications driven by the aerodynamic gains they yield. During testing at Barcelona's Circuit de Catalunya at the start of the year, Mercedes' technical director, James Allison, described the development strategy: 'For us, [W11] was all about trying to make sure we don't run out of development steam on a package that worked pretty well for us last year.

'If we had continued merely to add flourishes to the 2019 baseline, we would have found some gains, but in all likelihood diminishing returns would be kicking in by now.

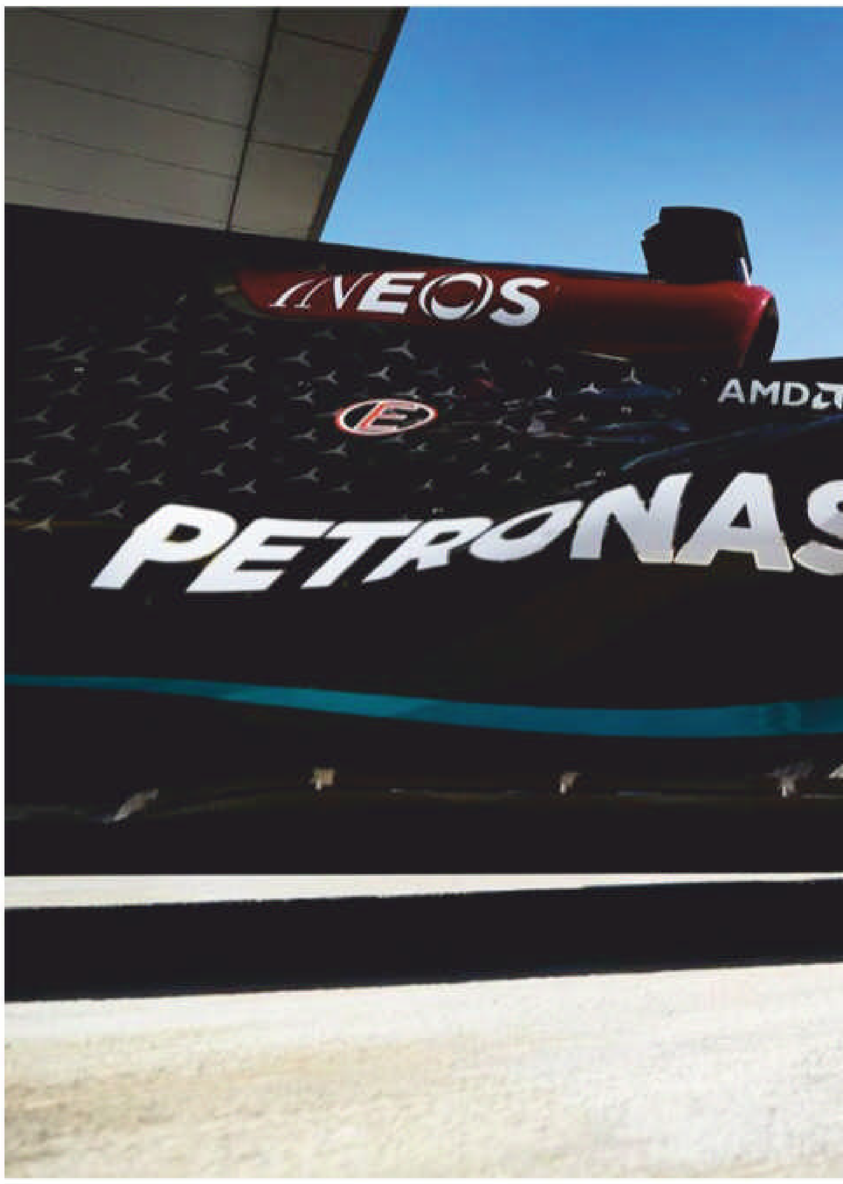
'We wanted to change aspects of the concept of the car – aspects that would be completely impossible to change within a season – to give us a more fertile platform for the new season [2020]. We tried to make a few well-chosen architectural changes to keep the development slope strong, even though the regulations are now a little bit longer in the tooth.'

Development teams

Mercedes' engineering team structure allows it to evaluate development in parallel and series. At the top level, development calls happen in what Mercedes call The Vehicle Performance Group, which has the most senior engineers in it. They will discuss what is happening race to race, what the team are learning from the car and what they should look at to improve performance. That will set the broad direction of where development goes.

With wheels steered and the direction of the car changing relative to the ground, it's hard to characterise how the W11 behaves in yaw. Mercedes says it aims for overall aerodynamic balance during cornering, rather than developing specific areas of the car for these scenarios

One of the most significant changes Mercedes made for the W11 was a shift to the side impact structure position



Underneath the Vehicle Performance Group are several engineering squads that focus on specific areas, and then break down into subgroups within.

Mercedes has a specific structure in place to characterise and tackle each type of development operation. If it is a geometry argument, that conversation would be between the Vehicle Dynamics Group and the Mechanical Group, working out what the trades would look like for any development ideas in these areas.

When it comes to a more aerodynamic component, like a sidepod for example, the

Positioning the side impact structure in the 'mid-height' position raised the sidepod inlet. This philosophy makes for a higher c of g for the associated components, but an overall net gain was found in the aerodynamic benefits

aerodynamicists will identify an opportunity and then discuss that with the Vehicle Design Group and examine the implications of the proposed changes – particularly whether it would pass the various tests and any additional weight implication.

That discussion would give Aerodynamics a rough number in terms of the performance they need to find for that change to break even in overall lap time. They then take the design ideas, create them, take them to the wind tunnel for testing and, depending on what comes out of that, will then decide whether that particular development has legs or not. If it does, the development continues.

John Owen is chief designer on the Mercedes-AMG Petronas F1 team. He is the architect of the car, making sure the various teams make the right trade-offs between different areas of performance, be it aerodynamics, power unit or vehicle dynamics. The buck stops with Owen, and he consults the Vehicle Performance Group to discuss whether specific projects are worth doing or not. Owen works alongside Mercedes' technology director, Mike Elliott, to bring together design and technology to formulate the best on-track weapon the team can design.

At the end of each season, the working groups come together to work out the development direction of the car. Mike Elliott explains: 'We often analyse and re-evaluate everything. Ultimately, when you are successful, the most significant risk of changing something will be that you might break it. The challenge you are facing is you don't have all the answers, and Formula 1 car design is not something where you can work out all the formulae and come up with the magic solution.

'These cars are complex, and the reality is you cannot take one bit in isolation and develop that. You have to have an overall philosophy of how you think is best to design a car for the application, and then you try to learn how it works and to develop it in a positive direction.'

2020 design changes

One of the most significant changes Mercedes made for the W11 was a shift to the side impact structure (SIS) position. The W10 had what is known as a high SIS position. That was redesigned and shifted to a mid-height position on the W11. The change was motivated by aerodynamic gains that, through the analysis of the working groups, Mercedes found outweighed the extra weight this structure requires to meet the stiffness needed in that area.

Elliott explains: 'This mid-height SIS was a theme we saw in the pit lane, something we didn't have and wanted to explore. Lowering the SIS yields indirect gains as it does not generate performance, though it frees up other areas so we could have the opportunity to try something different. It was a small change in position but a big enabler to other gains.'

> **For us, [W11] was all about trying to make sure we don't run out of development steam on a package that worked pretty well for us last year**
> *James Allison, technical director at Mercedes F1*

Lowering the SIS raised the sidepod inlets for the radiators located within them, which in turn raised the c of g, which is obviously not great for car performance. However, it improved airflow through the heat exchangers in the sidepods, which meant the team could run smaller radiators.

In turn, the team adjusted the amount of air ingested into the roll hoop for cooling to coincide with changes made to the sidepods.

Even this seemingly innocuous change was an intricate compromise, as Elliott explains: 'The car needs a physical amount of cooling, so the question is how do I best get that? Am I better off using sidepod radiators or better off with a radiator fed off the centre line in the roll hoop? The flow you get high up entering the roll hoop is very clean, very efficient, but positioning radiators that high up isn't ideal for the c of g. The ratio of sidepod to roll hoop radiators is a narrow trade to make.

'Additionally, the radiator layout is dependent on the route of the fluids that need cooling, and the position of the systems that need cooling under the bodywork. If the cooling route crosses both the centre and the sidepod then it is possible to distribute the cooling fluid flows across both and therefore make the most efficient layout for each cooling circuit. However, sometimes the position of systems forces one solution.

'That solution also depends on the chosen heat exchange medium. In aerodynamics, we'll know what the trade looks like for the porosity of the radiator, the total mass flow through the car, and what that costs in aerodynamic performance.

'We will know what a given type of radiator, with its fin density and the material's thermal coefficient, will deliver in heat rejection for a given amount of mass flow, and we know what that would cost us in weight, size and volume. Then we have to optimise between those.

'It sounds like quite a complex problem with lots of parameters, but actually it's not that difficult to solve. When you come up with a solution, that gets you 90 per cent of the way there, and then you optimise your way around that in development.'

Aerodynamic changes

Much of the aerodynamic development put into any Formula 1 car revolves around controlling the wake of the front tyres by using the wing end plate, the furniture on the top of the front wing and the brake duct to pitch the wake out and prevent the car from ingesting it.

The last few seasons have seen a variety of different approaches across the grid. The Mercedes front wing philosophy has seen its wing elements remain at a relatively consistent height across the width of the wing. This technique differs to its rivals, many of whom have focussed on the inner portion of the wing for downforce, steeply sweeping the outer parts downwards, with a focus on wake control.

The W11's front wing sees the top element reduce in height slightly towards the outboard section, which likely works together with the curved trailing edge of the end plate to promote outwash.

In an attempt to reduce the likelihood of tyre damage, the rules around the front wing end plate saw a minor change for 2020. The leading 50mm must now be made wholly of carbon fibre, with any metal fasteners or inserts sited at least 30mm rearwards from the leading edge. This rule change yielded very little difference to the front wing end plates of the W11 when compared to the W10, aside from the addition of a small wing profile on the centre of the end plate's outer face.

Of greater note is the unique nose design of the Mercedes, which has a slotted skirt that came into play last season and has carried through to the W11. The nose and the skirt underneath it generate some very complex interactions with the air coming off the front wing, as Elliott explains: 'Our nose design tries to manipulate tyre wake and get the Y250 structures to the bargeboard behind. The equations of fluid motion are elliptic, which means everything in the flow field affects everything else. Therefore, it is all interacting, and so there is no concept of being able to separate flow features apart.

'Different teams have different ways of managing that and, if you look at the complexity of the bargeboard structures these cars are carrying, it is a good indication of the complexity of the underlying flow field that is there.

'We manipulate the flow with everything we are doing on the inboard sections of the wing, but we're also manipulating it with lots of other bits as well. It all comes together to give us the solution we want, rather than one dominant feature.'

Mercedes was the first team to adopt the narrow, low-nose design in the field, with several other constructors following suit for the 2020 season. Here you can see the 'skirt' behind the nose that controls the Y250 vortices

Holistic strategy

When it comes to cornering aerodynamic performance, Elliott describes Mercedes' development strategy as holistic.

'We want to know how the balance of the car is changing throughout the corner, and what upsets the aerodynamics of the car and how stable the flow field is. That includes how it performs in yaw, roll and pitch because they are all working at the same time in a corner. Even if you consider the changing of flow direction relative to the ground, you are entirely affecting the flow over the rest of the car as you do that.

'Changes to the flow field will be completely different between conditions. As such, we don't look at any one state and investigate what happens at x yaw with x steer and x roll at x ride height to find how that affects performance on track. We look at all the elements together. There is no point developing a car that is quick in turn 10 in Barcelona when it's rubbish everywhere else.

'Not only do we want the best performing car, we also want to produce one that's balanced and consistent to the driver and works with the mechanical set-up of the car.

The front suspension is designed around aerodynamic components on the so-called 'cake tins', which influence the flow fields. These aerodynamic parts need space to work, and moving the wishbones up and out of the way achieves that

The rear suspension is designed to interact with the rear floor and rear tyre squirt. Note the dirt on the bodywork, indicating airflow converging on the rear centreline and exiting through the upper and lower rear suspension wishbones

The wishbones are about as high and as flat as possible now, and this technique has little to do with the suspension

Mike Elliott, technology director at Mercedes F1

Car behaviour can be controlled in the set-up of the suspension, ride height, how we want to make use of the tyres and so on.

'Driveability, predictability and tuning scope has seen a huge drive in Mercedes over the past couple of years to rid us of the 'diva-like' characteristics our cars used to have.'

Suspension aero

Much of the front suspension design Mercedes has on the 2020 car is an evolution of that which is now commonplace in the paddock, which sees the front wishbones as high as teams believe feasible. Positioning the wishbones in this configuration provides a significant structural challenge, though a positive aerodynamic trade off. The impetus behind the high wishbone concept is to provide a cleaner path for the Y250 vortices, which shed from the inboard ends of the front wing elements at their intersection with the regulation-controlled central portion of the wing.

Elliott explains: 'The wishbones are about as high and as flat as possible now, and this technique has little to do with the suspension, it's more about the cake tins [carbon covers over the front brake systems which support the calipers]. More specifically, it is about how we're using bits on the cake tins to influence the flow fields and giving those bits space to work. Moving the wishbones up and out of the way does that.'

The W11's rear suspension is designed the way it is because of how it interacts with the rear floor. Again, Elliott clarifies: 'The interaction here is between the tyre seal area, as well as all the bits on the rear cake tin furniture, that optimally balances the flow field. It's a complex interaction that manipulates different flows. That's all I can say there.'

DAS re-boot

The big news from Mercedes at the start of the season was the Dual-Axis Steering (DAS) system. It was revealed to rivals on the second day of pre-season testing in Barcelona, when onboard footage showed Lewis Hamilton moving his steering wheel fore and aft on corner entry and exit respectively. It was observed that the steering wheel movement coincided with a change in toe angle of the front wheels, with pushing generating a toe out (similar to the default position for a Formula 1 car) and pulling bringing the wheels inwards to a more neutral toe position.

At the technical conference in that afternoon, Mercedes' technical director, James Allison, coined the system DAS.

Elliott explained to *Racecar* that DAS was a separate project initiated in the performance areas of the business, and was a combination of efforts by the Vehicle Dynamics and Vehicle Concept groups.

'There wasn't anything in particular in terms of car behaviour that Mercedes wanted to improve with the introduction of DAS. It was implemented as a tuning tool, offering a dynamic way to improve in all areas, and this is a consequence of the fact that we are far down the line on these regulations.'

Seasonal change

The 2020 season started late, and that influenced not just the tracks Formula 1 went to, but also double headers, with almost all races occurring at different times of the year than they would normally. Places like Austria, where the season started in July, and Barcelona in August saw unusually hot conditions, while races in Germany in October were significantly colder than any other race in the current era. Elliott insists development of the car was unaffected by this unexpected change to the calendar.

'After Australia was cancelled, the factories closed, and the calendar changed. We didn't see a huge chance to start afresh, so we went with the package we designed for 2020 initially. We used driver-in-the-loop simulation to optimise what we've got for the new circuits and the forecasted conditions.

'For the significant anomalies, like Germany in October, many assumed we made considerable changes to optimise the operation of the car running in those ambient temperatures. We didn't, we had that range from the start of the season. Germany was cold, but I think if you look at where we are in winter testing, it's not hugely different, so we design to able to run at a range of temperatures.

'The way you would make use of the package you've got in terms of cooling, and how you deal with the tyres, changes as a result of the ambient conditions. The circuit temperature was an interesting challenge this year, but we didn't change the car, we just changed the set-up to get the best out of it.'

Development strategy

Traditionally, Mercedes has outperformed the competition by a process of massive development over the winter, producing a robust car for race one of the incoming season, followed by consistent but less potent changes compared to its rivals throughout the season. This development strategy has seen the team start strong, and its competitors only start breathing down its neck in the mid-season to the closing stages of the championship.

At a conference at the Nürburgring in October, Mercedes Formula 1 team principal, Toto Wolff, explained that Mercedes had stopped the development of its 2020 Formula 1 car 'a long time ago', as questions arose about its diminishing advantage over Red Bull at the German circuit.

'Mercedes had not released any updates for the W11 for a number of races,' he stated. 'This strategy is very thoroughly thought through, because not in every championship can you afford to close the book early.

'But the rules changed quite a lot for next year and in that respect, like in previous years, we decided to switch to next year's car midway in 2020. This is why you can see the shifting performance between the teams. We always have a very strong start and middle of the season, and then whoever continues to develop is strong at the end.'

From the technical side, Elliott articulates, 'As you develop a car, the one you've just created is the best car you've ever produced, because you've got the most knowledge. It is on target for what you want to achieve in terms of the numbers you set at the beginning of the development period. But yet, you're picking those numbers based on what you think you need to find, based on what you believe your development slope looks like, and where you think everybody else is.

'In some ways, you're setting a target based on the knowledge you've got of where you *think* you can get. So, when you hit that target, it doesn't mean anything. The reality is that we're not in this to try and produce the best absolute product, we're in this to try and produce a product that is better than our opposition's.

'You can't judge whether you've done an excellent job or a lousy job without seeing what everybody else has done. So, what generally happens is we sit down at the end of the season and ask ourselves where we *think* we need to be, given the regulations. And then we look at *how* we've been developing, what sort of slope we *think* the competitors are developing on, what we *believe* our time gaps are and then kind of shoot for a point in space, using the timeline of race one. And that's where we head.

We're not in this to try and produce the best absolute product, we're in this to try and produce a product that is better than our opposition's

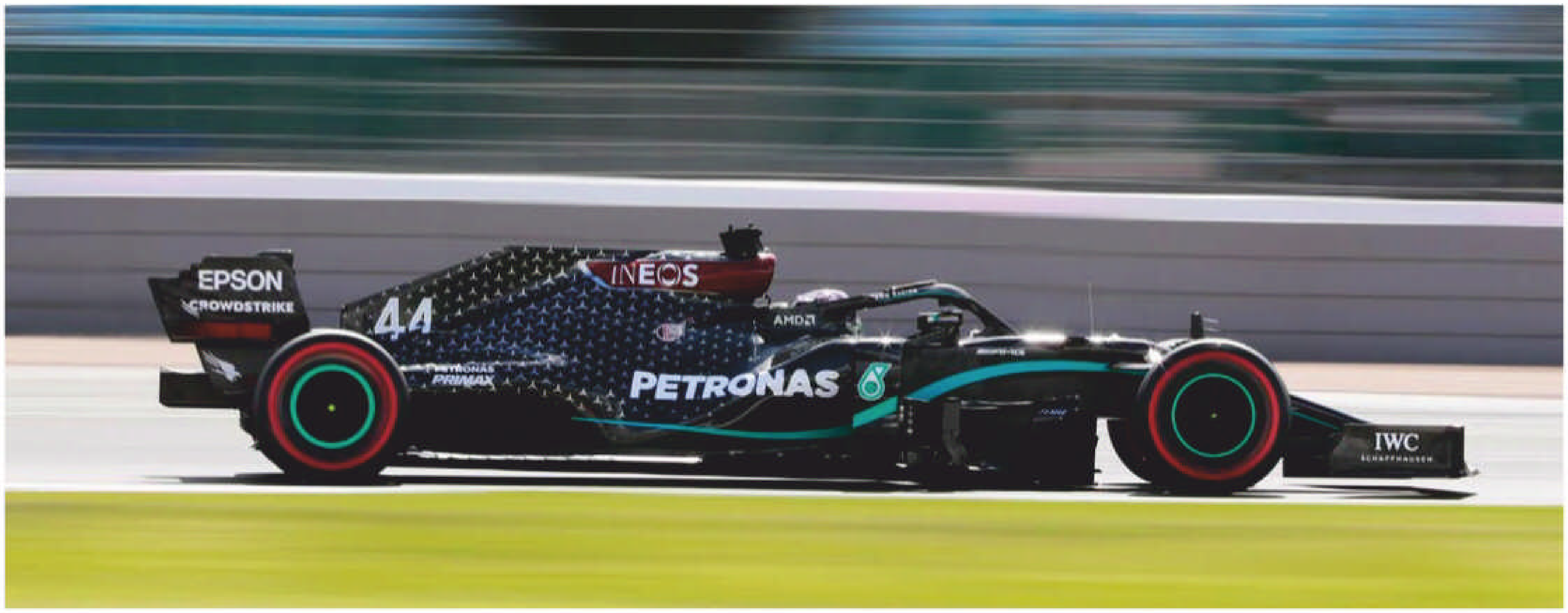
Mike Elliott, technology director at Mercedes F1

'In some years, I've been involved in car projects where we've exceeded those targets and not been quick enough. And I've been in years where we've come under and had a rapid car. So, did we achieve our target? Well, for me, we achieved our target when we got to the first few races, and we saw our performances was where we wanted it to be.'

As part of a cost-saving measure resulting from the Covid-19 pandemic, teams will only be allowed to develop specific areas of the chassis for 2021 via a token system. Mercedes deem the regulation changes critical, and are front loading the development in the hope of maintaining dominance over the rest of the field at race one.

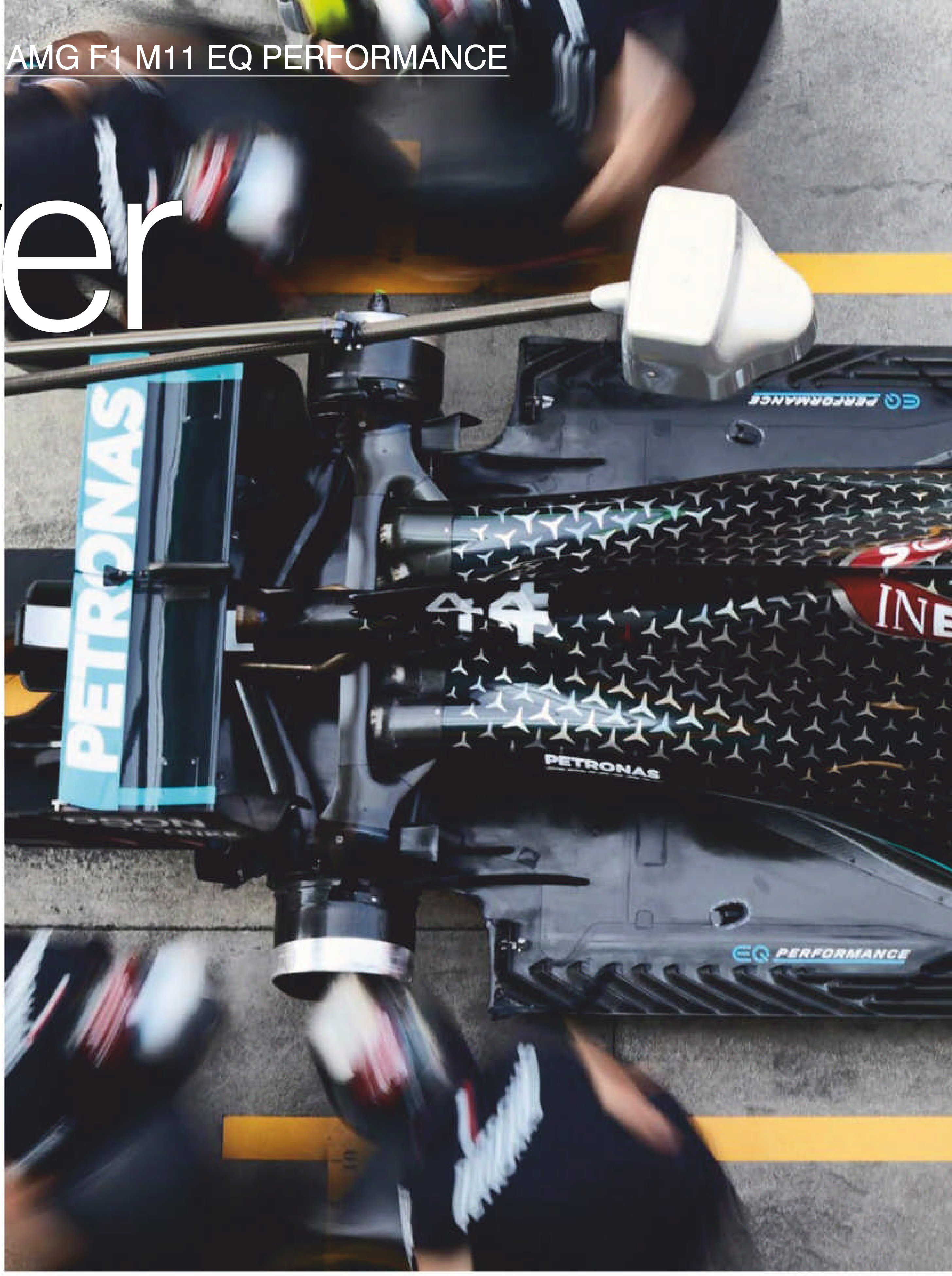
'There will be quite big aerodynamic changes,' confirms Elliott. 'These have been put in place to try and limit downforce and will have big consequences. I think they are big enough in terms of the effect on lap time that whoever does the best job of developing out of those and recovering the performance will have the best car.

'I don't think we can sit comfortably thinking we've been quick this year. We need to do a good job over the winter, and we need to get as much performance out of those regulation changes as we can.'



The rake of the 2020 Mercedes AMG F1 W11 EQ Performance, to give the car its full official title, is higher than it was in previous seasons

Power play



Incremental development is the philosophy in F1, and Mercedes has proved it's at the top of the engine game

By STEWART MITCHELL

Mercedes' seemingly insurmountable power unit output advantage over the competition at the beginning of the current hybrid era has eroded with each passing year of the current regulations, and the gap between each power unit has narrowed. However, Mercedes remains at the top of the pack in 2020, with only Honda power in the back of the Red Bull RB16 piloted by Max Verstappen seeming to disturb the two black arrows on outright pace on track.

By combining live GPS data with sector time and lap time information with the FOM data streams off each car, teams can work out how much power another car is using in each sector, and therefore the energy strategy, and even the efficiency of the competitions' hybrid systems. Using such analysis, it is hypothesised there is a 25bhp delta between the best of the field and the worst.

There were no significant changes to the Formula 1 power unit regulations for 2020. But, in early June 2020, Formula 1 management froze development, restricting the four engine manufacturers to a certain number of specifications of internal combustion engine and hybrid elements for the remainder of the current power unit period, ending in 2025.

The regulation revisions stated that for 2020 no changes are allowed to any component within the internal combustion engine, turbocharger, MGU-H, fuel or oil, and only one change is permitted to any of these parts for the 2021 season. Additionally, only one specification change to the MGU-K, control electronics package and energy store is allowed between the start of the 2020 season and end of the 2021 season.

Dyno testing

On top of these development restrictions, the FIA also brought stricter dyno testing limitations into force for 2020. Teams are now limited to nine full-fired, multi-cylinder engine tests, or a fired engine and transmission together, including full-car dynos (but excluding single-cylinder engine testing). until the end of the 2025 season.

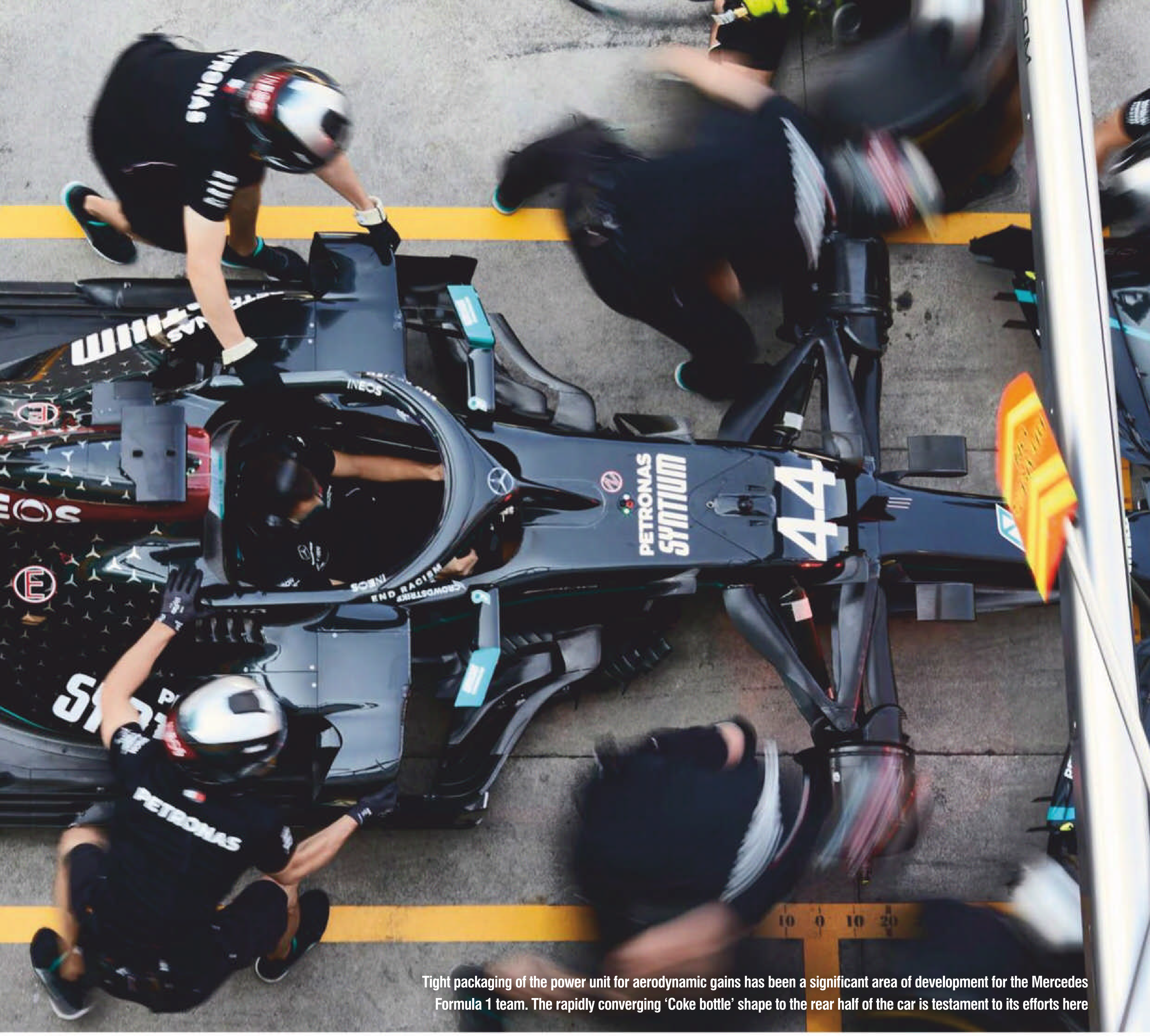
However, Mercedes completed much of its development on the 2020 power unit before pre-season testing. During that time, the upgrades were designed and tested as much as the old regulations permitted.

The power unit allowance remains at three per driver per season. This is coupled with higher power demands year-on-year, owing to increased downforce on the car. This affects the power unit, both structurally in terms of the output requirement and subsequent loads on the parts, as well as reliability as the engine must sustain this output for longer.

With Formula 1 being a fuel flow limited formula, set so the fuel mass flow to the engine may not exceed 100kg/h at any point, with a maximum allowable fuel load of 106kg to last a race distance, the regulations force teams to design engines to maximise combustion efficiency as a function of the thermal characteristics in the cylinder.

Efficiency gains

The largest contributor to the performance gains in Mercedes' power unit comes from combustion development and friction reduction. Each year, engineers come up with



Tight packaging of the power unit for aerodynamic gains has been a significant area of development for the Mercedes Formula 1 team. The rapidly converging 'Coke bottle' shape to the rear half of the car is testament to its efforts here

The largest contributor to the performance gains in Mercedes' power unit comes from combustion development and friction reduction

a more efficient and reliable running engine, which allows gains to be found in tighter packaging and integration. These, in turn, mean improvements can be found elsewhere.

To this end, the ideal combination from a combustion efficiency perspective is a high compression ratio (Formula 1 permits up to 18:1) with a lean mixture, with that mixture burnt as rapidly as possible. That's the theory, but it is challenging to achieve in practice.

As ever in technological development, it's more a case of 'win-lose' than outright 'win-win', so teams must be selective in their development strategies to ensure the 'win' is of greater magnitude than the 'lose', so the net result is an overall improvement.

Coupled with the fact the single-stage turbocharged, 1600cc, 90-degree V6 engines are supported by a hybrid system, strategies include MGU-H and MGU-K development.

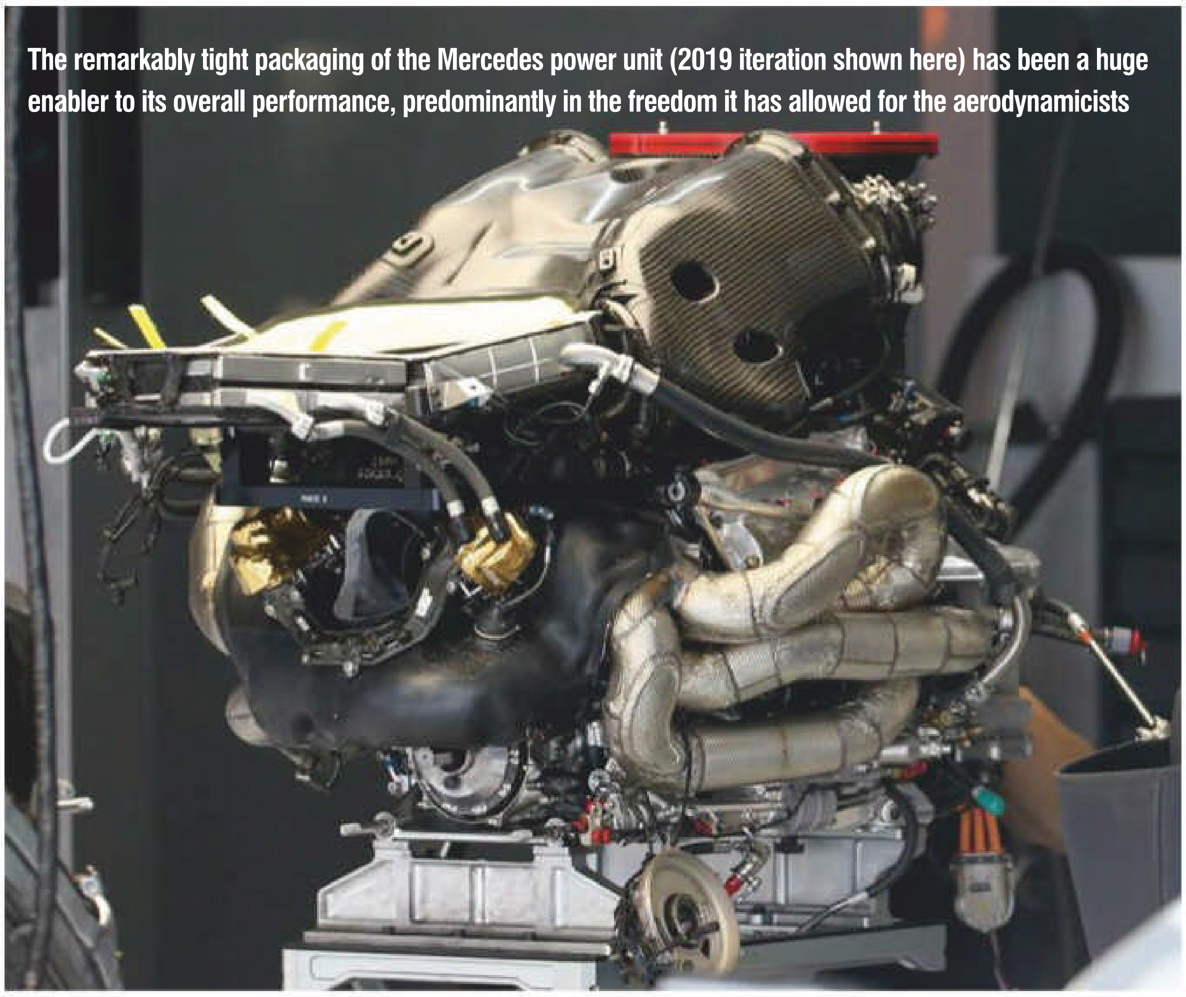
There are many ways teams can reach the 1000bhp overall output required to be competitive in contemporary Formula 1. Mercedes' route to meet the challenge has seen the manufacturer on top since the start of the current engine era, and doing so from its Brixworth, UK site, with the help of Daimler's R&D group in Stuttgart.

To maximise combustion efficiency, Formula 1 teams typically work on the combustion process itself, and then build the engine that enables that around it. In turn, the development teams' efforts aim for the engine to reject as little heat as possible to reduce the amount the aerodynamicists have to channel through the radiators.

Combustion development

It remains true that, while there are many energy type conversions in the Formula 1 power unit (and many transmission loops in the power unit), the most lucrative one is from fuel to useful work at the crankshaft. Consequently, heat (and therefore energy) release in the combustion process is where most of the development resource is spent.

In the quest to convert all the chemical energy in the fuel into kinetic energy, teams are constantly chasing down losses in the process, including ideal gas and combustion time losses, as well as other waste factors such as friction and heat. In an ideal world,



The remarkably tight packaging of the Mercedes power unit (2019 iteration shown here) has been a huge enabler to its overall performance, predominantly in the freedom it has allowed for the aerodynamicists

Exhaust header development revolves around how the spent gas energy converges onto the turbine side of the split turbocharger that runs through the centre of the vee (2019 PU shown here)

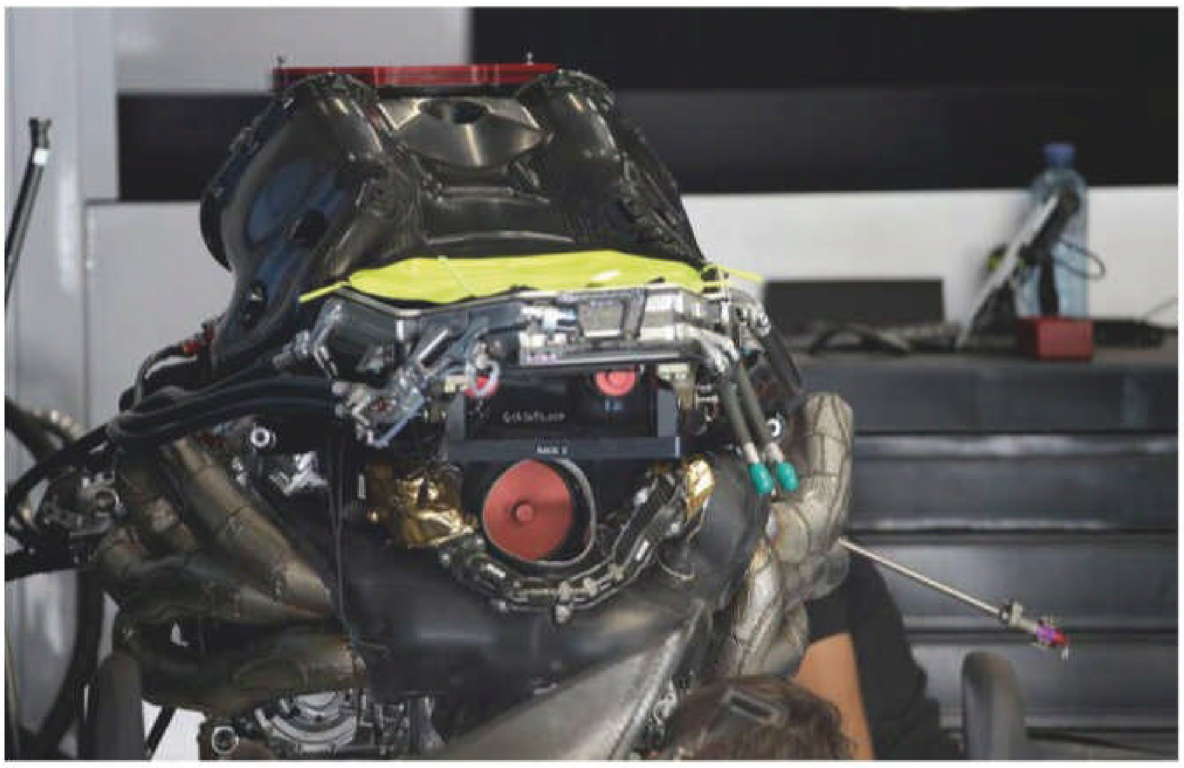
they don't want any of the available energy doing anything other than pushing the piston down to drive the crankshaft.

Additionally, any energy not converted to crankshaft rotation they want going into the turbocharger, rather than out of the exhaust system as spent heat energy. A consequence of those targets is that heat rejection must be managed very well. A power unit where heat rejection is going up is one where losses are going up relative to the fixed amount of energy coming from fuel flow.

Mercedes' internal combustion engine programme has focussed heavily on thermal efficiency. Despite being long into the current hybrid regulation set, the manufacturer has found more ways to tackle gas losses, improve combustion gas formations and the ratio of specific heats that define its chemical to kinetic energy transfer efficiency.

'With energy input limited, the way the fuel and air that enters the engine and combusts needs to be considered very carefully,' explains Mercedes-AMG High Performance Powertrains (HPP) managing director, Hywel Thomas. 'Over the whole period of this regulation set, we've been striving to understand the combustion process to the best of our abilities, and develop techniques to be able to use what we theorise we gain in combustion, and then develop the engine in several ways to get the thermal efficiency to climb slowly.

'We've made some changes this year on the piston rings, and the positioning of the piston rings relative to the crown. Also changes to the details around the gas slots and drain slots. These changes are to look after blow-by and oil consumption.



As much as the internal combustion engine development is critical, so too are the electrified elements of the powertrain. The MGU-K can be seen underneath the exhaust manifold on the left of this picture of the 2019 PU. Mercedes has gone to great lengths to increase the maximum deployment time of its MGU-K

'These changes have not yielded a considerable amount of percentage in terms of the combustion efficiency individually, but each element is either a direct contributor or an enabler elsewhere. At this point in the development cycle, it's very much about putting those details together with collections of information in other areas to creep up the thermal efficiency. It's the whole package we're looking to develop and, where you can find small gains in lots of places, it's leading to a more considerable overall increase. It's this technique at this stage in the regulations, rather than any significant concept change or revolutions we're chasing.

'It is that continual development, and through learning and pushing just that little bit further, we've made gains in every area.'

Over the whole period of this regulation set, we've been striving to understand the combustion process to the best of our abilities

Hywel Thomas, managing director at Mercedes-AMG HPP

Formula 1 engines require complete combustion to happen almost instantaneously at TDC, with blow down complete by BDC. The process used to develop that combustion speed revolves around manipulating geometries and parameters in the combustion chamber, and selecting the fastest combustion process highlighted from CAD modelling and then CFD simulation of the chamber. That is followed by correlation to ensure the output on the real engine will match the simulation.

'Once we know the digital model of the combustion chamber is translating, we can make subtle changes to some of the inputs [fuel injection and spark parameters, for example] and the geometries in the combustion chamber,' continues Thomas.

'An example of this is on the piston crown and the valves. Changes made here on the digital model were validated using CFD to understand how that is affecting combustion. We try different scenarios and form an understanding of the tuning that generates the most efficient combustion. Then we verify the final solution on the real engine.'

Spontaneous combustion

The chaos inside current Formula 1 engine combustion chambers, combined with the extreme pressure and high compression ratios, creates an environment that can produce controlled spontaneous combustion. Contained within certain crank angle degrees around TDC, this can provide what is termed Homogenous Charge Compression Ignition (HCCI). In short, this is a form of combustion in which uniformly dispersed air / fuel mix is compressed inside a cylinder to the point of instantaneous auto-ignition. This phenomenon is a huge enabler in the quest for ultra lean-burn operation and high thermal efficiency. It is not exclusive to Formula 1, but applies to all systems that require a highly efficient IC powertrain.

Most HCCI engines currently in operation use very complicated components, such as cylinder heads with built in pre-combustion chambers and electronically-actuated control systems that accurately monitor and control the temperature of the working fluids throughout the intake and compression cycle.

Currently, there is little in the public domain about HCCI use in Formula 1, with teams only confirming that, in some cases, the pressure increase that occurs as a consequence of combustion gas chaos causes spontaneous combustion, as opposed to flame front combustion, and, in some cases, that is welcome. It's fair to say that control of such a complicated condition in any engine, but particularly a race engine that sees such extreme full-throttle duty cycles as Formula 1 engines do is an extremely challenging environment to achieve.

Technical Directive 37

With the introduction of Technical Directive 37, multiple engine modes for qualifying and races were banned, and with it went Mercedes' Strat 2, or so-called 'party mode'. As qualifying is for outright pace over a single lap, considerations for the deployment strategy beyond the start / finish line go out of the proverbial window.

In qualifying mode scenarios, teams would essentially leave the pits with a fully charged battery and end the hot lap with the battery completely depleted, with little consideration given to the laps that follow. There is also a damage function in such a mode that protects the power unit if exploited for more than a single lap without time to recover energy and cool the electrical systems.

Until Technical Directive 37 came into force, at Monza Mercedes had scope to accommodate a situation where its drivers could run qualifying modes during a race stint as part of its overall strategy. In such cases, as with qualifying, the battery would be depleted to its lowest safe state of charge with the view that the pace would gain track position value, whether it be leapfrogging in the pits or clearing traffic on the same lap.

'There are races on some circuits where we are running almost the same mode as before the Technical Directive came in,' confirms Thomas. 'As long as you're doing it every single lap of the race and qualifying, you can do it. Our power unit is very robust, but there are still considerations in the damage this causes to the engine, should we use a full qualifying mode at every circuit.

'That isn't the case, though, and there are other areas where [the mode] is very different from what we were running before the Technical Directive came in. I'm not going to give you a number of kilowatts, or a percentage difference between where we were and where we are now nominally.

'What I will say is we have not suffered specifically because of Technical Directive 37. It has just forced us to be more thorough with our engineering processes.

'It is about having more robust simulation, more robust engineering, more robust prove out and then more robust manufacturing and supplier quality as well as assembly process to make the product more consistent. That has been the real lesson from the Technical Directive from our perspective.'

> We have not suffered specifically because of Technical Directive 37. It has just forced us to be more thorough with our engineering processes
> – *Hywel Thomas*

But if HCCI can accurately be controlled here, it would likely be most beneficial during harvesting conditions (steady rpm with variable load) and off-throttle moments. As to whether Mercedes uses HCCI that is controlled in such a fashion Thomas would not confirm, only reiterating the Mercedes' PU uses spark assistance to start combustion.

Cylinder strategies

To further improve the overall cycle efficiency of the internal combustion engine, F1 teams also use various strategies to run engines on any number of cylinders, from zero, when the MGU-K is in full recovery and the throttle is shut, to six. The job of the engineers is to understand the attendant dynamics of that on the crank train and everything after it, as well as the impact on the intake and exhaust / turbo loop, and the tuning implications.

There is a journey from the driver being on full throttle to coming off it, and then a journey back onto the throttle where there is the opportunity to go from six fired cylinders down to zero, or anything in between, and then the same on the way back up. Exactly how Mercedes implement this is also a closely guarded secret, but the technology is known to be used. It is no doubt a significant contributor to the success the team has acquired in this current hybrid era.

> **Formula 1 teams also use various cylinder strategies to run engines on any number of cylinders, from zero to six**

Friction losses

Just as important is to extract the maximum possible force from the chemical to kinetic energy conversion when the fuel and air combust in the chamber, and key to this is reducing frictional losses. Consequently, surface finishes have been a significant area of development for Mercedes, especially since the 2018 reduction of engine allocation.

'There have been developments in coatings in recent years, and coatings have been essential in allowing us to reduce friction, increase torque and reduce the stress on rubbing components,' confirms Thomas.

'As for the oil properties, we work closely with Petronas, and have several programmes with them looking at friction and how we can change the lubrication regimes and match the oil to what's happening in the engine to reduce that friction.

'The surface finishes we can now achieve on the components that require fluid film separation have significantly improved, and this has allowed us to change the viscosity of the engine oil to make it more efficient.

'The base viscosity of the oil is something we bear in mind, and it's not always the case that a lower viscosity oil will make the engine have less friction. Along with some of the very detailed formulation work we do with Petronas, matching oils to how the engine is running has certainly made steps in reducing the overall friction of the engine.

'Like many things, it's that continual development, and learning to understand the complexities in the relationship between components, that creates a gain. Working with Petronas brings incremental changes that we understand and can characterise properly, rather than large steps.'

While having peak performance output from the internal combustion engine is critical to performance, Formula 1 engines must be thought of in the context of an integrated powertrain, which combines the internal combustion engine and the MGU-K and turbo compound loop / MGU-H electrical machines.

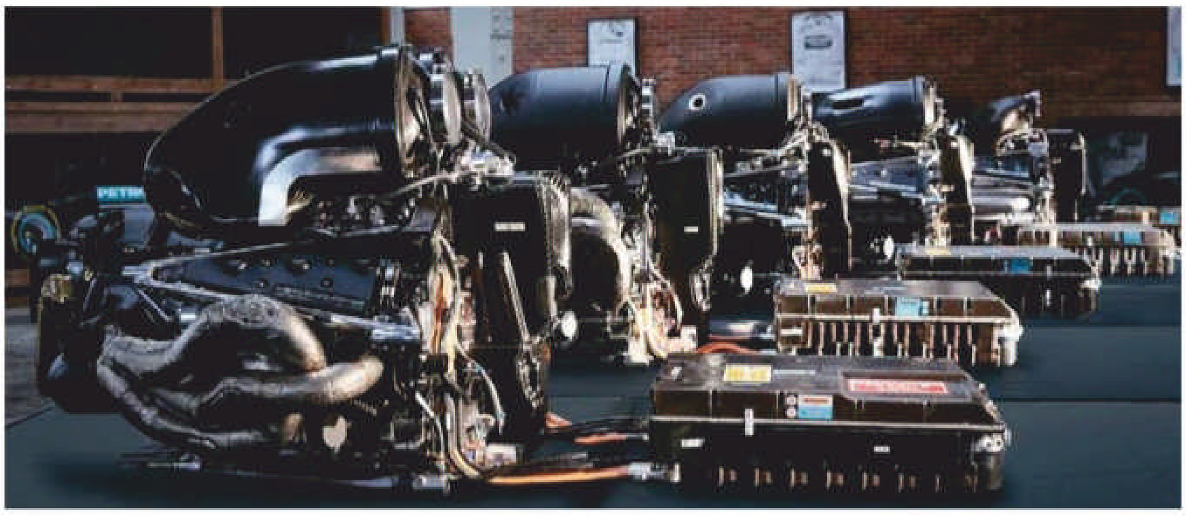
Electrical strategy

The route to good lap times is to maximise overall efficiency at all times, but in some cases it may actually be better for overall lap time to sacrifice some internal combustion engine performance to boost the power of the electrical machine in a given track sector.

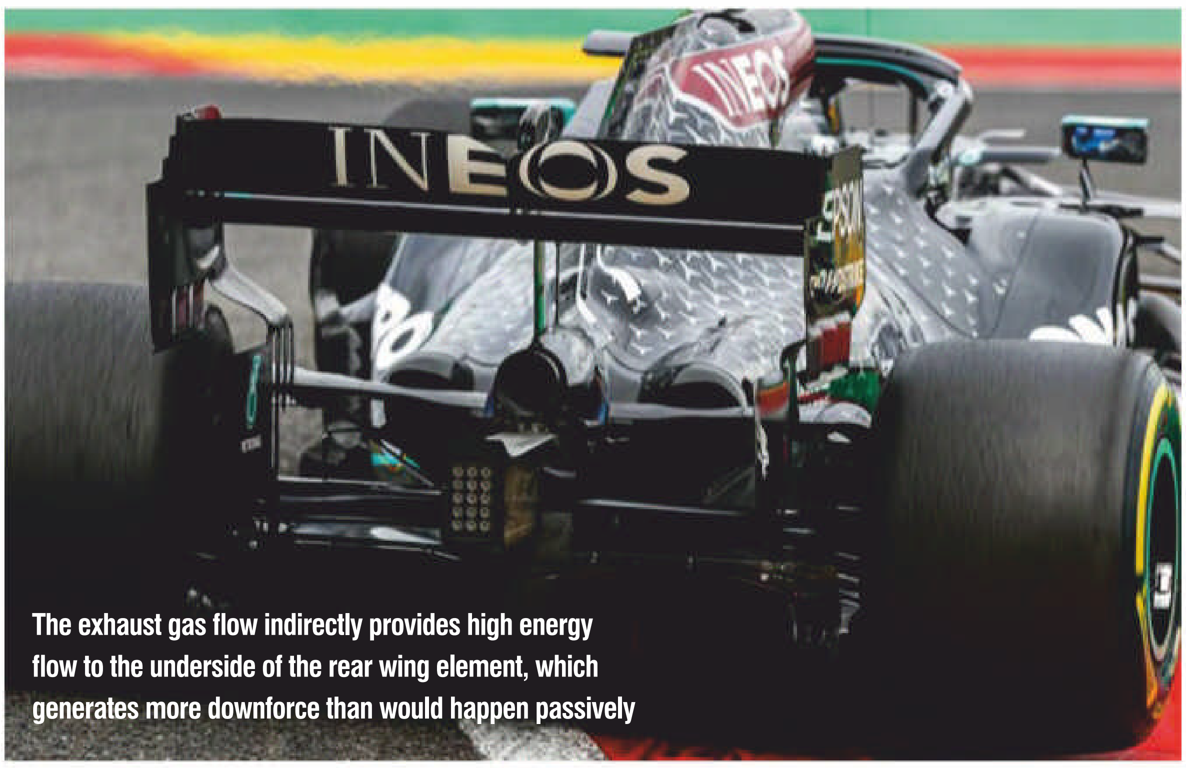
With this in mind, quick lap times insist on the best possible power at the start of the straight, having deployment power from the MGU-K available whenever the car is not traction limited, and keeping the electrical deployment for the longest time possible.

However, on many Formula 1 circuits, it is not necessary to have maximum deployment for all of the straight as harvesting for peak deployment at the exit of an upcoming corner may yield better overall power strategy and lap time gains than the car's Vmax. In other words, high average torque counts.

As Formula 1 regulations cap the power output of the MGU-K, teams aim to ensure the turbo compound loop is robust and efficient enough so that at all of the race circuits, the MGU-K is on all of the time it can be, with the battery state of charge not swinging dramatically from lap to lap. Improving the efficiency of that loop is key.



Battery technology has seen significant improvements throughout the duration of this regulation set (2018 PU and battery shown in the forefront here)



The exhaust gas flow indirectly provides high energy flow to the underside of the rear wing element, which generates more downforce than would happen passively

Because of the sheer amount of energy and power flowing through the hybrid systems, small opportunities to improve efficiency yield massive rewards

Mercedes' mantra for the hybrid system development is that the target output should be an average of the peak deployment on each circuit on the calendar, with some headroom for reliability and push-to-pass potential during on-track battles. The team noted that each year full power MGU-K time went up incrementally, partly as a function of hybrid system development, but also thanks to improved aerodynamics, suspension and understanding of the tyres.

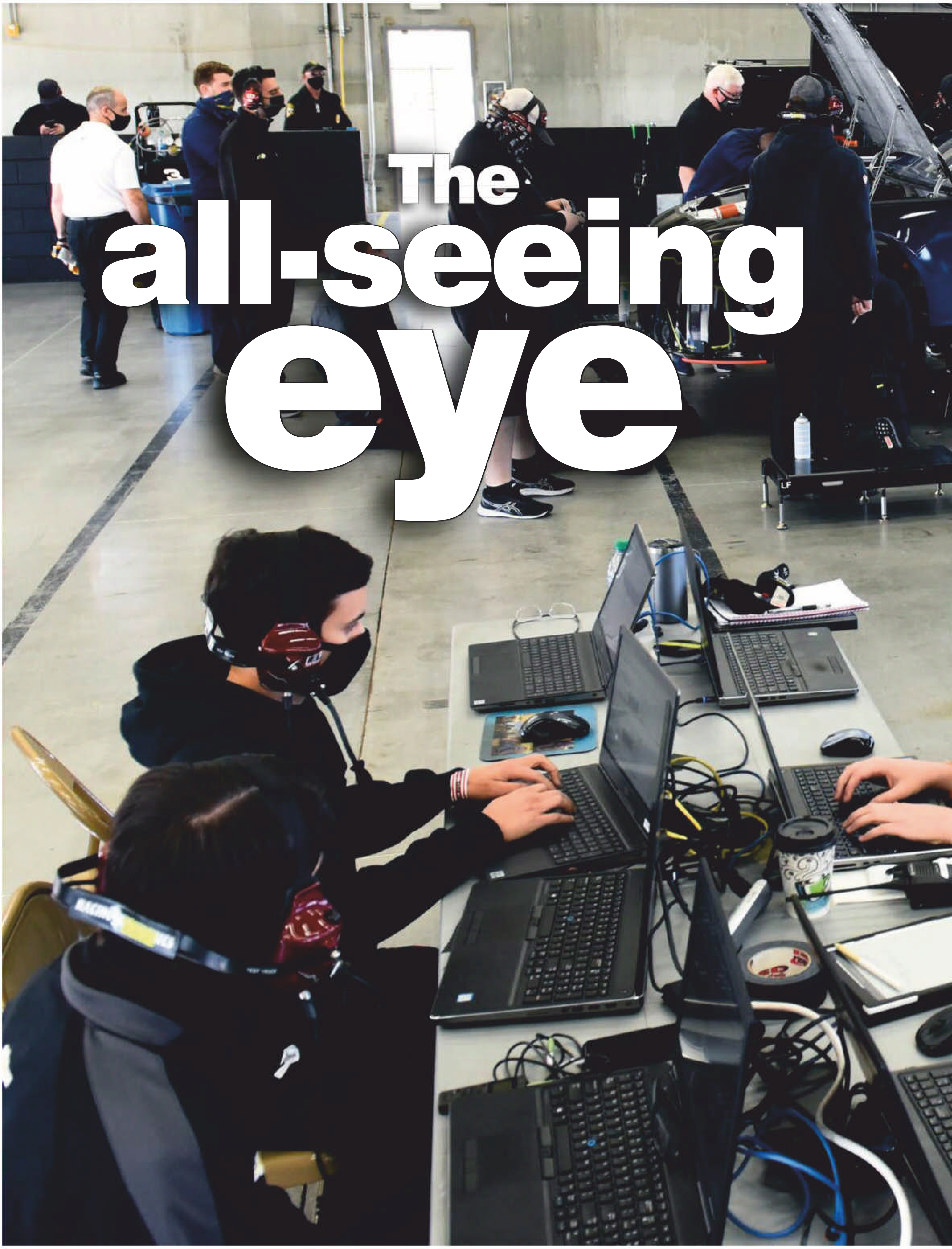
As to the question of whether teams have now reached a point where MGU-H / MGU-K development is starting to plateau, at least within the current regulations, Mercedes is adamant there are still gains to be had. The consensus is still that small opportunities to improve efficiency yield massive rewards. For example, improving the efficiency of the turbo compound loop increases the amount of MGU-K on time, which, in turn, means the system is more resilient to derating in high output scenarios.

Overall, it seems Mercedes has managed to maintain its electrical energy advantage over its opponents in 2020, primarily thanks to the MGU-K on time potential being longer than its competitors. You can see that in the races by looking at where the other cars suffer derate, and velocity consequently drops off when compared to the Mercedes' seemingly relentless power delivery.

Another area Mercedes identifies as advantageous to its power unit success is its integration of the electronics systems. The team has worked exceptionally hard to make sure all controls for the power unit are in one box, and all the systems in one place, avoiding having to use additional cables and connectors. This optimisation lowers weight and volume, reduces complexity and offers greater reliability.

How Mercedes' development of the car and engine will progress in the remaining years of the current power unit formula remains to be seen. But, with seven championships under its belt, it's clear Mercedes remains the team to beat.

The all-seeing eye



The final calls on strategy still rest with the crew chief, but they are now backed up with considerable engineering resource

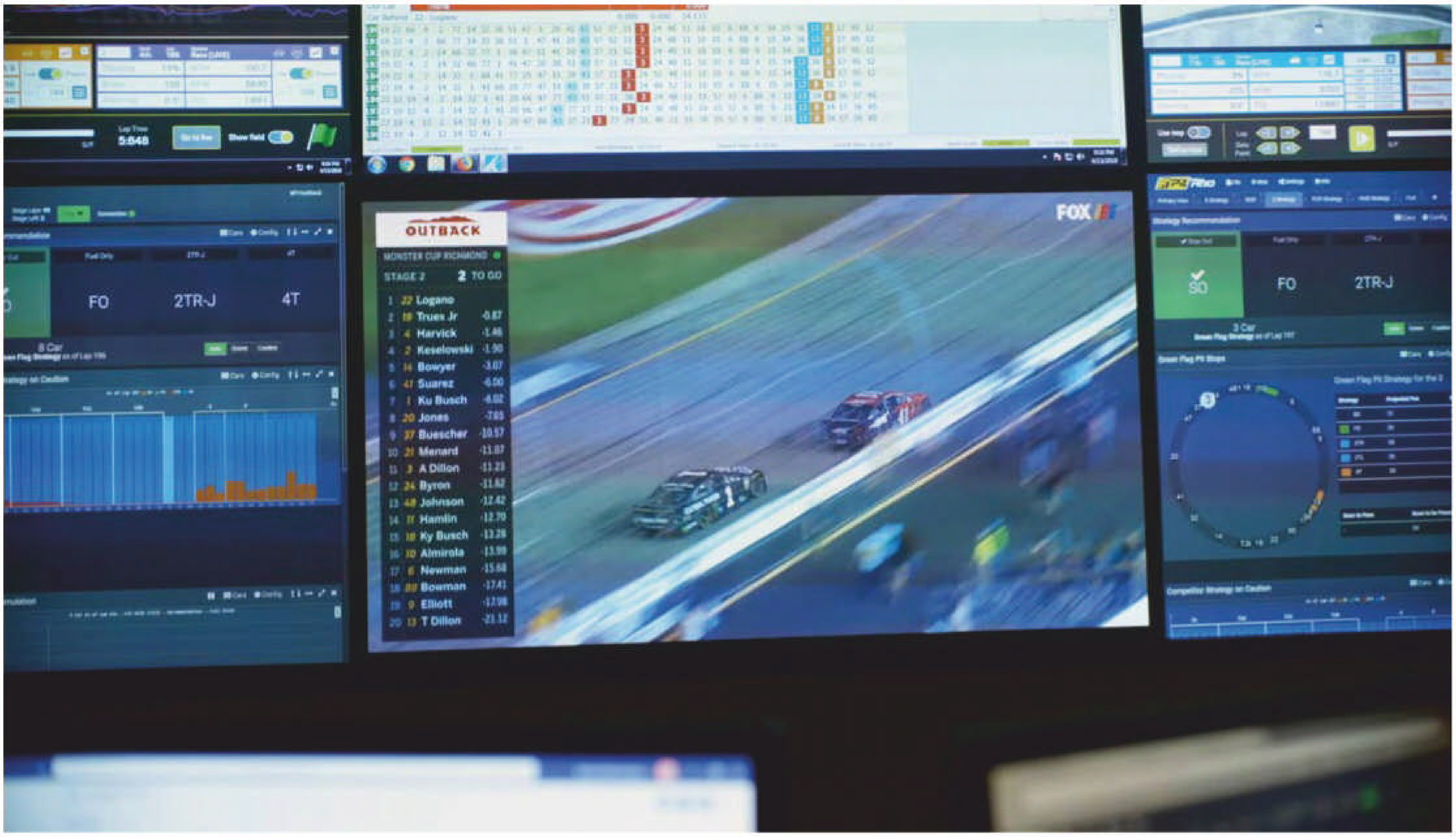
Data analysis is increasing rapidly in NASCAR's development processes, from race strategy and studying the competition to next generation car improvement

The role of the NASCAR crew chief is changing, thanks to the relentless march of artificial intelligence

By LAWRENCE BUTCHER

The traditional image of a NASCAR crew chief is an analogue one, sat atop their pit box in isolation, reliant on an accumulated internal databank to make judgement calls on race strategy. The modern reality, however, is a far more digital affair.

The big, manufacturer-backed teams now utilise mission control operations similar to those pioneered in Formula 1 and, while telemetry data is still far sparser in Stock Car than single-seater racing, teams do now have some real-time feeds from their cars. Importantly, they also have data on what their competition is doing.



A snap shot of the type of data display seen in a modern NASCAR team's mission control. Combining all this data with intuition and experience makes for a winning combination

The final calls on strategy still rest with the crew chief, but they are now backed up with considerable engineering resource, including machine learning-based artificial intelligence (AI) strategy systems.

The march of AI is everywhere, its scope seemingly endless, be it at the core of autonomous driving technology or harnessed by companies to figure out our personal habits. AI, and the machine-learning algorithms that underpin it, have revolutionised the way data is processed, and it is only natural race engineers are looking to use this to their advantage.

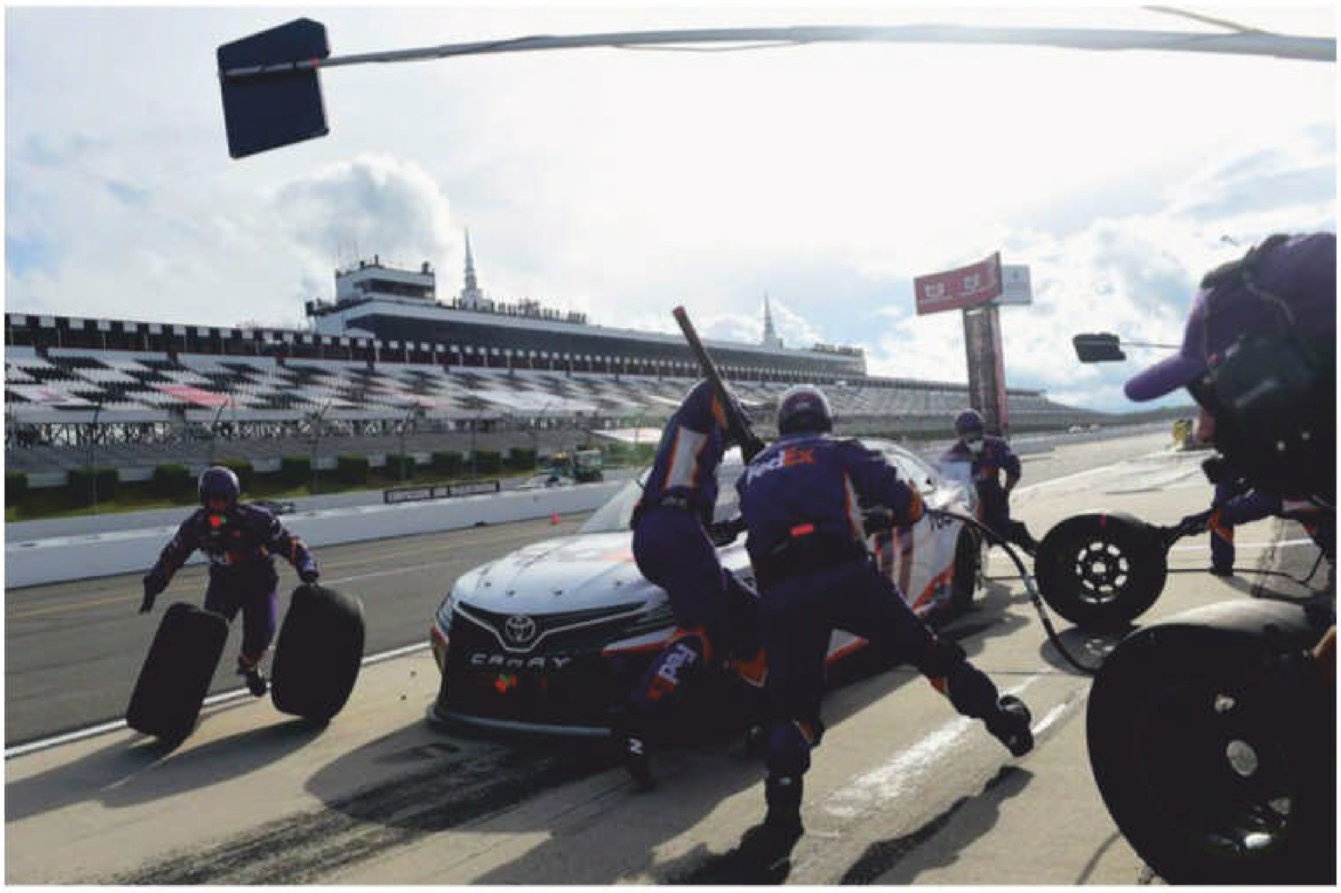
In the case of GM-backed teams in the Cup series, they are doing so through an application called Pit Rho, developed by specialists Rho AI.

Racing roots

According to company founder, Josh Browne, a former Chrysler engineer and NASCAR crew chief, 'The idea was lifted straight from Formula 1.' Back when Dodge was still in the Stock Car game, there was a degree of knowledge exchange between racing programmes that fell under the Daimler Chrysler umbrella and Dieter Zetsche, then head of Daimler, had an interest in NASCAR.

At the time, Browne was involved with Evernham Motorsports (running Dodges), a very engineering-led team in the 2000s, and had the opportunity to visit the then McLaren Mercedes team in the UK.

'Some of us in the Vehicle Dynamics Group got to go over quite a bit,' he recalls.



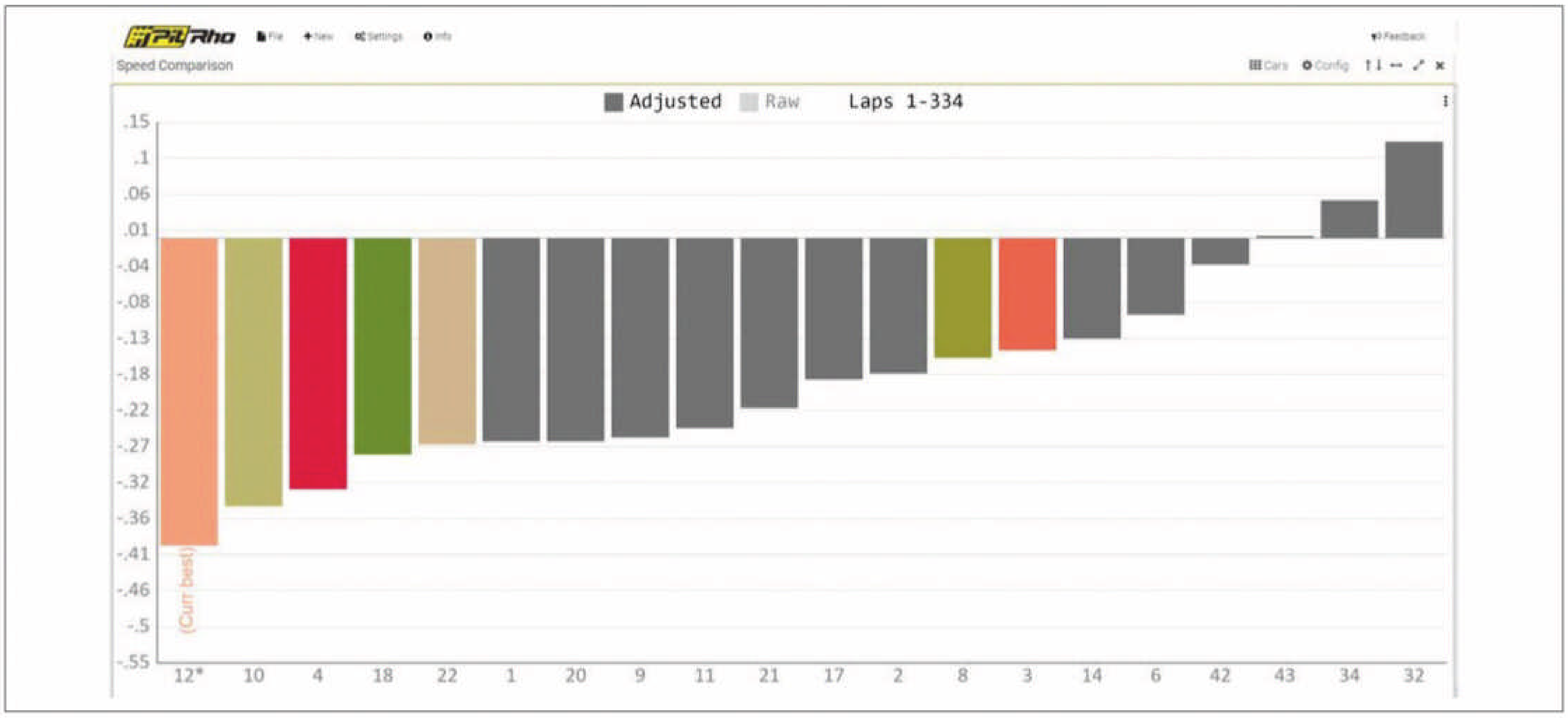
Calling a pit stop strategy incorrectly can lose a race for a fast car, but get it right and it can push a slower car up the field

'One of the things we saw, which is likely ancient technology now, was their method for predicting the outcome of a race. Starting from the first practice laps, based purely on lap times and sector times, and then refining the projections lap by lap.'

He spent his last two years in NASCAR as chief engineer with Red Bull, which entailed more experience of F1, by which time, 'several of the McLaren strategists had migrated to RBF1, and the concept of predicting outcomes had evolved. I got to see that evolution.'

> **A more competitive field, longer races, and a lot of full-course cautions… add an element of statistical chaos to any modelling work**
>
> *Josh Browne, Rho AI founder*

An example data screen showing speed comparisons, suggested strategies and predicted competitor strategy. Having an inkling of what your opponents may be planning is invaluable



Pit Rho display window showing a speed comparison between the field at Texas, the race where the system offered a strategy that led to a surprise win for a slower car

The seed of an idea was sown to apply a similar approach to Stock Cars but, notes Browne, 'the NASCAR problem is harder than in F1. Subjectively speaking, you have a more competitive field, longer races, and a lot of full-course cautions, which add an element of statistical chaos to any modelling work you do.

'You don't need a PhD to reasonably predict the outcome of an F1 race better than 50 per cent, if you just take the running order after the first lap. That's not the case in a Stock Car race.'

Nevertheless, he still felt it was possible to use modelling to call NASCAR races, but a lack of willingness to invest meant it remained a pipe dream.

An academic interlude

Browne left the world of racing and decided to undertake an engineering PhD, during the course of which he met a group of people from MIT who wanted to develop a gambling model to predict the outcome of NASCAR races. 'There were four or five sports books in Vegas where you could bet head to head on driver subsets. For example, Jeff Gordon vs Jimmie Johnson at a particular track. The MIT guys knew I was generally unaffiliated, with a technical and quantitative background, and they wanted to build a machine-learning model to gamble on NASCAR.'

This took Browne back to his earlier ideas of an F1-style predictive model and, following a call to long-time colleague, Eric Warren (now head of GM's NASCAR activities), to access current timing data, coupled with his own 10-years plus of historical data, the basis for a machine-learning model was developed.

Though initially basic in terms of data inputs, the model proved effective, as Browne explains: 'If you have the lap times for enough cars over a long enough period of time, you can start to extract meaningful, interesting, sometimes valuable trends. You can estimate traffic density, as you know when cars cross the start / finish line and how far apart they are from each other.

'From that, you can begin to extract aerodynamic and traffic density sensitivities, and from there develop track feature sensitivities. For example, you know that aerodynamic sensitivity at Bristol is going to be different to Indianapolis.

'Our gambling model very quickly evolved into a predictive analytics tool. We were making money with the gambling project, and it was fun, but it wasn't as interesting as building a model we could actually use in competition. We didn't want to do both, because there could be a perceived conflict of interest there.'

General Motors saw the potential in the idea for its racing programmes and funded the initial development work, and has been a partner of the resulting company, Rho AI, ever since.

So it was that Browne returned to the racing fray, with the company working initially with Eric Warren, then at Richard Childress Racing, before expanding to encompass all GM-backed teams.

Data integration

The next stage in the system's development was the integration of pit stop data. To achieve this, a number of tools were designed to extract pit stop information from publicly available sources, specifically a number of fan-facing, second-screen apps.

'We then knew who pitted when, and what they did. Such as take on tyres and fuel, or just fuel, that sort of thing. We had a small army of data collection people that were really good at that and we had an active data set built around pit stop information,' explains Browne.

It was at this point, in 2017, that the system had its first high-profile success. 'We made a call that everyone else thought was really risky and stupid, and left Ryan Newman out late on old tyres from eighth or ninth place. We won the race. After that, people got a lot more interested in harnessing machine learning-based tools to drive strategy.'

In the past two years, NASCAR has opened up the data streams it derives from the cars' ECUs and dash-logger displays to teams, providing relatively low-resolution data on throttle position, steering angle, brake pressure, longitudinal and lateral acceleration and GPS coordinates. The important element in this being that all data, from all cars, is available to every team.

Initially, publicly available information was used to enhance the model with pit stop data. Integrating that broadened its scope

'From that, you can do a good bit of derived statistics, up to and including some vehicle dynamics metrics that are valuable in real time,' notes Browne. 'What helps in NASCAR, compared to F1, is that everyone is on the same tyres. Couple that with some reasonable assumptions around cornering stiffness and other suspension characteristics and you can make some deductions around tyre usage and lateral force generation at each corner.'

What this means in practice is that informed estimates can be made of each car in the field's performance every 0.2 seconds. 'You can then relate that to your car's lap time. What are the trends? Where do they rank in lap times? What is the slope to any trend? Can the lap times be attributed to performance issues?

'You can then inform the crew chief and race engineers on the pit box that they are currently, for example, the 11th quickest car on track at that point, and are losing most of their speed on corner entry at both ends of the racetrack, which may be due to an oversteer-type instability, so that's what they need to work on,' summarises Browne.

While a team might not necessarily like being told it only has the 11th fastest car on track, Browne stresses this is important when it comes to strategy. 'We wouldn't want to recommend an aggressive strategy to a car that is not that fast, which might temporarily put it out front, only for it to be back down the pack in a short time. Or worse, wreck.'

Significant features

Key to making the system work, and drawing on what is now 18 years' worth of data, is identifying which features of the data are most significant. 'We have to understand the

It is the system's ability to learn, on a lap-by-lap basis, and adjust strategy calls to suit the specifics of a given track at a particular moment in time, that makes it so powerful

dozen or so features that really matter, and then allow the system to learn those features as a race evolves,' concurs Browne. 'For example, we might identify that if you restart on the front row, in a car that is only 15th on speed, on older tyres, you can still win the race, because the adjusted speed from first to 15th might only be 0.15 seconds a lap, but it is worth 0.18 seconds a lap to start first.

'We actually won with Austin Dillon at Texas this year doing exactly that. It was because by that point in the race, we precisely understood the dynamics around lap time degradation, traffic density, everything like that.'

It is this ability for the system to learn, on a lap-by-lap basis, and adjust strategy calls to suit the specifics of a given track at a particular moment in time, that makes it so powerful.

The unusual situation around the 2020 season, where there have been no practice sessions before races, has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4
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placed an even greater onus on Pit Rho's algorithms, as Browne notes.

'We had to do a lot of aggressive machine learning at the start of the race to be able to make strategy calls like the one at Texas.'

There are, of course, a host of other factors that can evolve through a race weekend and season that must be accounted for. Track surface is just one example. Some tracks are visited twice in a year and, taking Phoenix as a case in point, the cars first run early in the season, and then again later when the track has been baked by an Arizona summer.

'We assume the lap times will be different from the first to second race at the venue, but we have to accurately quantify the difference once we have informed the models with historical data. So, as soon as the green flag drops, we start learning,' says Browne.

This approach also applies to changing conditions throughout a race. Over hundreds of laps, the position of the sun changes, altering track temperatures across a lap. More so in those races that run from day into night.

Even the ability of drivers to pass or be passed is considered. 'We have passing dynamics. How well can one driver pass, or how do they react when being passed by others? Which drivers are hard to pass? Can you identify whether a driver has made a pass just by their lap time?' observes Browne.

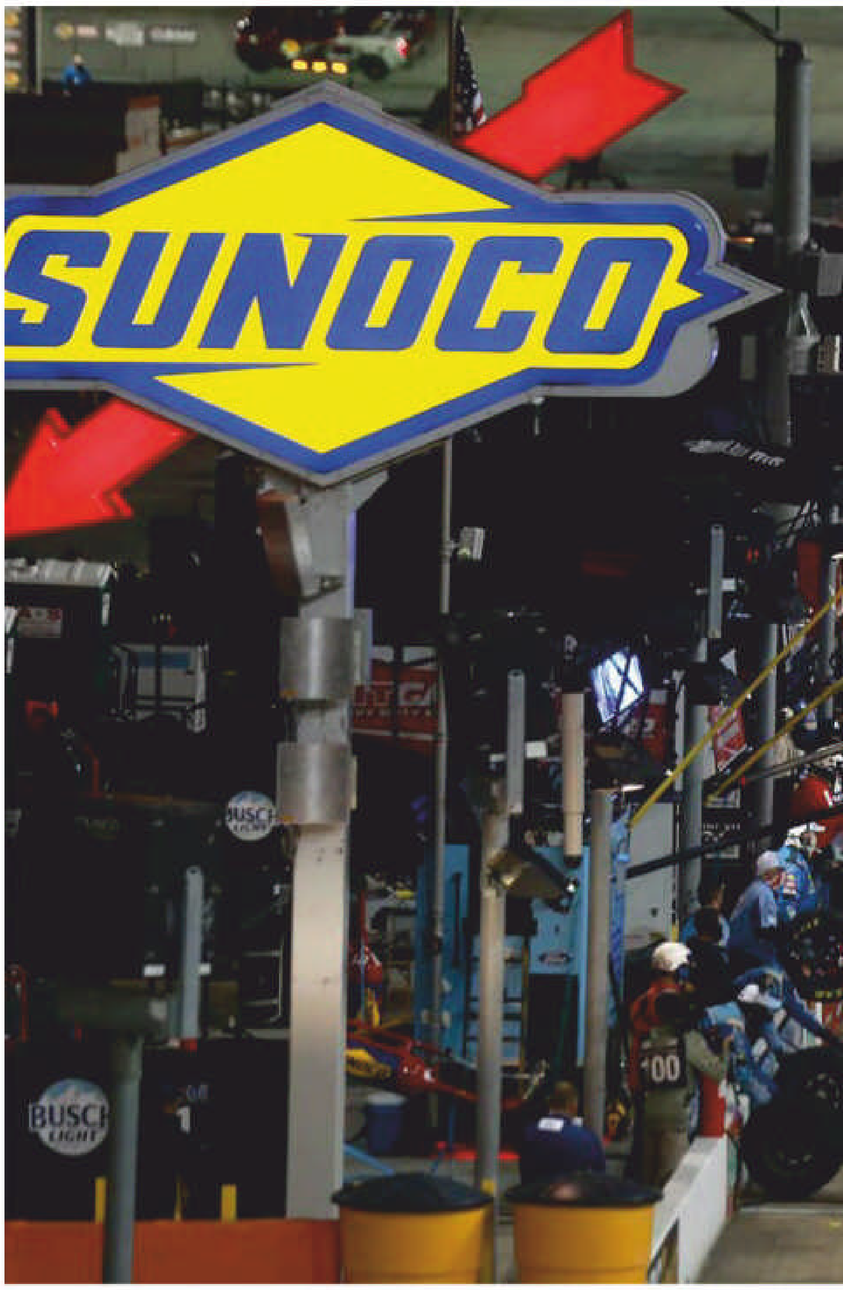
As soon as the green flag drops, we start learning

The top drivers tend to be quite adept in this area, knowing not to waste time battling to keep someone behind to the detriment of overall race position. However, he notes the one exception was every driver in the field used to slow down to pass Danica Patrick, even those usually unphased by passing.

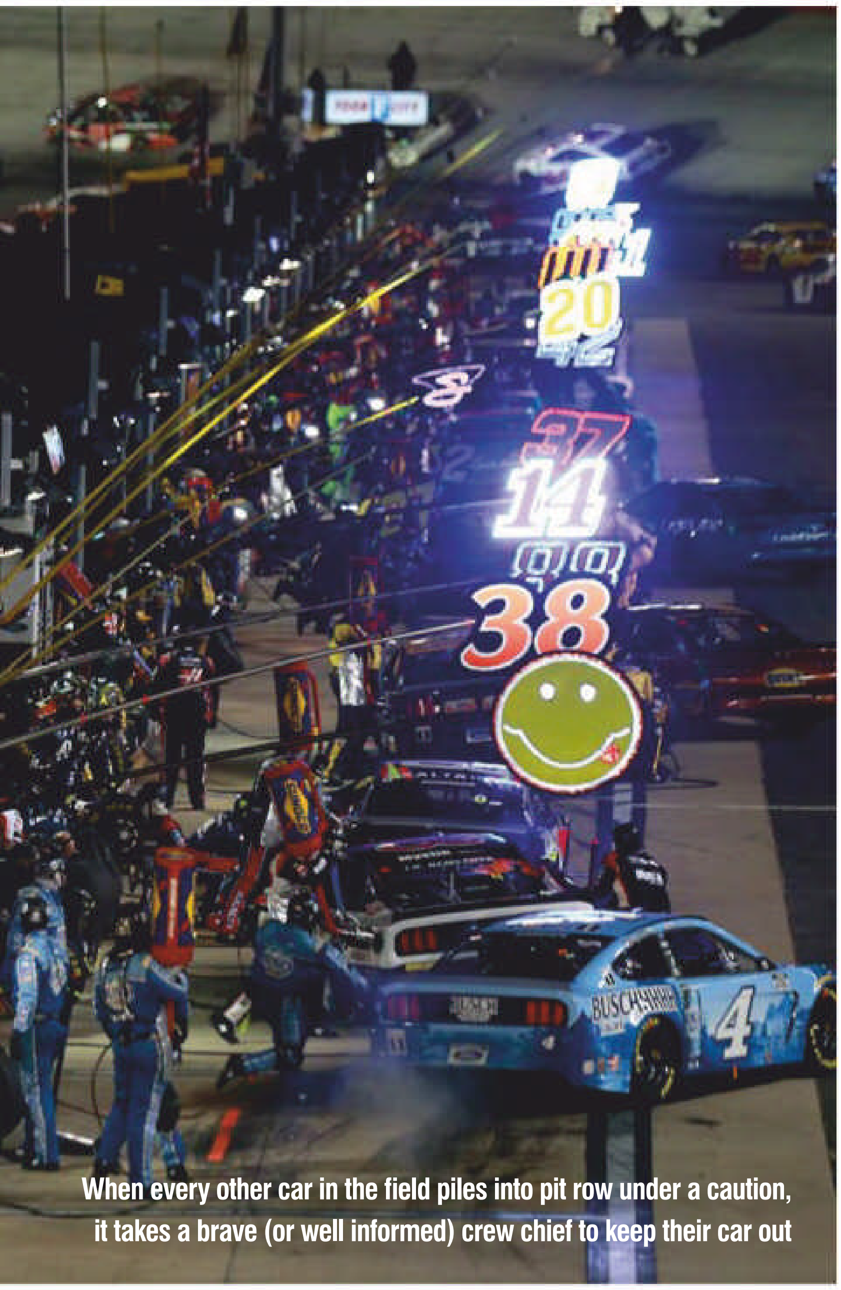
'It wasn't a statement about her being erratic, simply that other drivers perhaps seemed to subconsciously not want to risk wrecking one of the most popular drivers in the series.'

Old school acceptance

There is definitely still the outside perception that NASCAR crew chiefs are old school in their approach to running cars but, over the past two decades, Stock Car racing has become a sport dominated by engineering method. Even those that might potentially be viewed as set in their ways, borne out of years of hard-won success, such as Chad Knaus



The next stage in the development process is to take a data science approach to the recommendations the system makes, in order to give hard evidence to back up set-up changes



When every other car in the field piles into pit row under a caution, it takes a brave (or well informed) crew chief to keep their car out

The crew chief's view

Cliff Daniels was, until recently, crew chief on the no.48 car of Jimmie Johnson for Hendrick Motorsport and, for 2021, will run Kyle Larson in no.5. He is well accustomed to working with the Pit Rho system and made the following observations on how it has changed his role.

'The cool part is you're able to take a 10,000ft view and say, 'Okay, I know x based on empirical data that I've experienced, decisions I've made, outcomes I've seen based on a certain race or race strategy. When you then pair that with a machine that is literally crunching numbers in the moment, to the millisecond, based on all the different environmental variables and factors – speed, fall off, pace, competitive strategy, predicted competitor strategy – all these different aspects. It means you're able to look at both your own intuition and a tool that can predict an outcome. It really does open up your options.'

He too notes that the importance of such tools has increased with the arrival of stage racing.

'As we've gotten deeper into strategising around data points, and the way the stage formats of our races are, there's just been a much higher need for another way to look at the race, based on the outcome you're after.

'For example, if you don't have a car capable of winning, your outcome needs to be to maximise points. If you know you have a car capable of winning, you need to call the race to maximise your potential to have the track position at the end, to take advantage of your fast car. This means there's a couple [of] different philosophies and strategies that have come about as we all try to make the best calls from scenarios created by the stage racing formats.

'That's where this software has really come into play. Not only for us, but throughout the whole of the NASCAR garage.'

If you don't have a car capable of winning, your outcome needs to be to maximise points

(now VP of competition at Hendrick Motorsports), have, says Browne, been receptive to the power of data-driven strategy. 'You could probably place Chad Knaus in that 'old school' category, but he was a huge supporter of the system, because he knew the difficulty in making all of these decisions in real time.

'Once we explained the why – and we don't just give these guys one chart to look at, our interface has about 70 displays available, which explain the reasoning to support the recommendations being made – he was fully behind it. Guys like that, and others like Andy Petree [who crew chiefed for Dale Earnhardt, amongst others], are very intelligent experts in their domain and get it at a very deep level because, in their heads, they have a lot of data points.'

The introduction of the stage system to NASCAR… was a gift to data scientists, providing at least two solid data points in every race

On this final point, he admits that in the early development stages of the Pit Rho model, former Roush crew chief, Jimmy Fennig, was used as a yard stick, thanks to his seemingly innate ability to successfully call race strategies. 'When we were doing our historical analysis to build the model, he just had an affinity for the strategic side and so we would use him as our test for some of the data sets, asking, did we out run Jimmy?'

Browne wryly points out that it now only takes a couple of example races – where a disagreement with the system's recommendations can be proved to have been costly – to convince most of its merit.

Points mean prizes

The introduction of the stage system to NASCAR, though it may offend racing purists, was a gift to data scientists, providing at least two solid data points in every race.

'It changed everything for us. But it was a pretty easy change, because we already optimised for total points. If you're doing that, and we're telling you you're going to have these known inflection points throughout the event that are points earning opportunities, you build your strategy around that,' explains Browne.

The points awarded for stage wins can, and do, have a decisive effect on championship standings. Browne gives the following example: 'It took a little selling but, once you have a car that is running 25th at Bristol, which stays out when there is a caution thrown 10 laps before the stage caution, wins the stage, then pits, but still comes back out 25th, bagging 10 points in the process, people start to pay attention.'

Though well refined, those responsible for Pit Rho's development, and the teams that now use it, are constantly pushing to further improve its insights. For example, Browne admits that one area of ongoing investigation involves bringing elements of set-up change into the equation.

'Right now, we can tell someone where they are slow and why, and give them a strategy recommendation, but we want to take a data science approach to telling them what chassis adjustment(s) they may consider to make the car go faster, at the same time balancing the benefit of making that adjustment against any time losses in the pits, and telling when they should stop to make it.'

It is clear that the harnessing of technology such as that used by Rho AI is a game changer in Stock Car racing, giving crew chiefs and race engineers levels of insight that would evade even the greatest polymath. However, Browne is at pains to point out that it is still just a tool, and those that make best use of it will be the ones that not only understand it, but augment its usefulness with their hard-won knowledge and instinct.

My gang

The GT2 class is taking off, with four manufacturers now building cars and more coming. KTM launched its offering in October

By ANDREW COTTON

Revised aerodynamics and a new engine will give the drivers the straight-line speed they are looking for

German motorcycle manufacturer KTM, which has been producing the X-Bow and derivatives for the GT4 category since 2008, has taken the next step in its racing programme and developed a new car for GT2 aimed squarely at the customer racing driver.

Actually, the company has launched two cars. Alongside the GT2, KTM has also released the GTX, which is aimed at track day driving, the Creventic 24-hour race series and can also compete in the GT-Open and the former VLN series, based on the Nürburgring Nordschleife. The two cars, GT2 and GTX, are similar enough that one can be converted into the other using a conversion kit that will shortly become available.

GT2 was launched in response to the increasingly aerodynamically complex GT3 cars, which have become too challenging for many amateur drivers to race competitively. With more aero dialled onto the cars, the speed is made up in the corners rather than the straights, and the amateur drivers have been rapidly disappearing as a result.

Stéphane Ratel, promoter of GT racing in various series around the world, built his business on these drivers and so has taken steps to address the issue, launching a series for relatively inexpensive cars more suited to them, and both manufacturers and tuners have responded positively.

Audi and Porsche were the first to produce cars, the former producing the R8 LMS GT2, while the latter created a modern interpretation of the 935 based on a 911 GT2 RS road car. This year, Lamborghini has created a GT2 car from its base of the Huracan Trofeo, while McLaren's plans remain unclear, having designed a GT2 car but not yet built it.

With four different makes, including KTM, now confirmed, and with cars already sold, the series looks as though it could take off impressively in the next two years.

The need for speed

KTM's new car features a development of the lightweight tub from the X-Bow, but the car features revised aerodynamics and a new engine that will give the drivers the straight-line speed they are looking for.

With a price tag of less than €300,000 (approx. $352,000) and with a running cost of less than €7/km, the car has already proven a success at the tills. Development company, Reiter Engineering, sold its allocation for 2020 and is now taking orders for 2021.

Four layers of carbon fibre… produce a double-walled, two-part carbon fibre cell that weighs around 80kg

Talk of the GT2 class being allowed to compete against GT3 cars, which was Ratel's original plan, has so far not become a reality, despite the two concepts being able to produce similar lap times. GT2 drivers are unwilling to compete against the GT3 cars that race in the GT World Challenge events, or national GT series. However, the Frenchman confirmed at Spa that the GT2 cars, clearly capable of completing 24-hour races, would be invited to race in the Spa 24h race in the event of his GT3 entries dipping below 50.

Skin deep

The chassis for the KTM X-Bow was developed with Dallara in 2007, using four layers of carbon fibre bonded using epoxy resin to produce a double-walled, two-part carbon fibre cell that weighs around 80kg. For the GT2 and GTX versions, a development of that meets all FIA GT safety standards, thanks to the addition of an integrated steel rollcage.

The KTM cars feature a 'jetfighter canopy', a front-hinged system that allows the windscreen and roof to lift providing access to the cockpit. Such a system means the car does not need the roof hatch that was made mandatory in GT cars as access to a driver's head and neck is possible. Electronic door handles are backed up with a mechanical system in case of failure. A side window allows for escape should the car become inverted.

Built around a carbon composite monocoque, the KTM is capable of more than just GT2 entry, with the Spa 24h on the cards

Adding an integrated steel rollcage structure to the X-Bow carbon tub helped bring the GTX / GT2 up to FIA GT specification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Much of the downforce comes from the sculpted underfloor, with close attention paid to the front splitter and mid-section airflow

The top side of the car looks decidedly clean and there is a reason for that. Much of the downforce comes from the sculpted underfloor, with close attention paid to the front splitter and mid-section airflow. Naturally, the rear wing takes care of much of the adjustability of downforce at the rear, and two splitters are available to change the balance at the front.

Double down

'If you want rear downforce, you just add wing angle,' confirms Reiter Engineering boss, Hans Reiter, whose company developed the GT4 car for KTM and who was instrumental in the development of the GT2. 'The front splitter has a big advantage in that we have no radiator at the front. You can have another front splitter with a high ramp [at the rear, just ahead of the front wheels] and can double the downforce at the front if you need to.'

Airflow is channelled to either side of the cockpit and the outlets there have been closed off in the presentation car, although, says Reiter, if you want to dramatically increase the downforce you can open the sides and channel air out from the front wheels that way. It is a concept close to LMP1.

From the front, the car closely resembles a Le Mans Prototype and that, says Reiter, was deliberate: 'The air outlet at the bottom of the doors is closed, but you can open it. It is not big money to do that. If you want to triple the downforce, you simply open the aero.'

Much of the development work was done by Reiter and KTM, but they had help from Nick Galbraith, director of GT Motorsport, who worked on the Lamborghini Gallardo GT3 car. With extensive knowledge of designing and developing cars from GT3 to DTM, Super GT and Le Mans Prototypes with Toyota, he was perfectly qualified to help with the CFD design work.

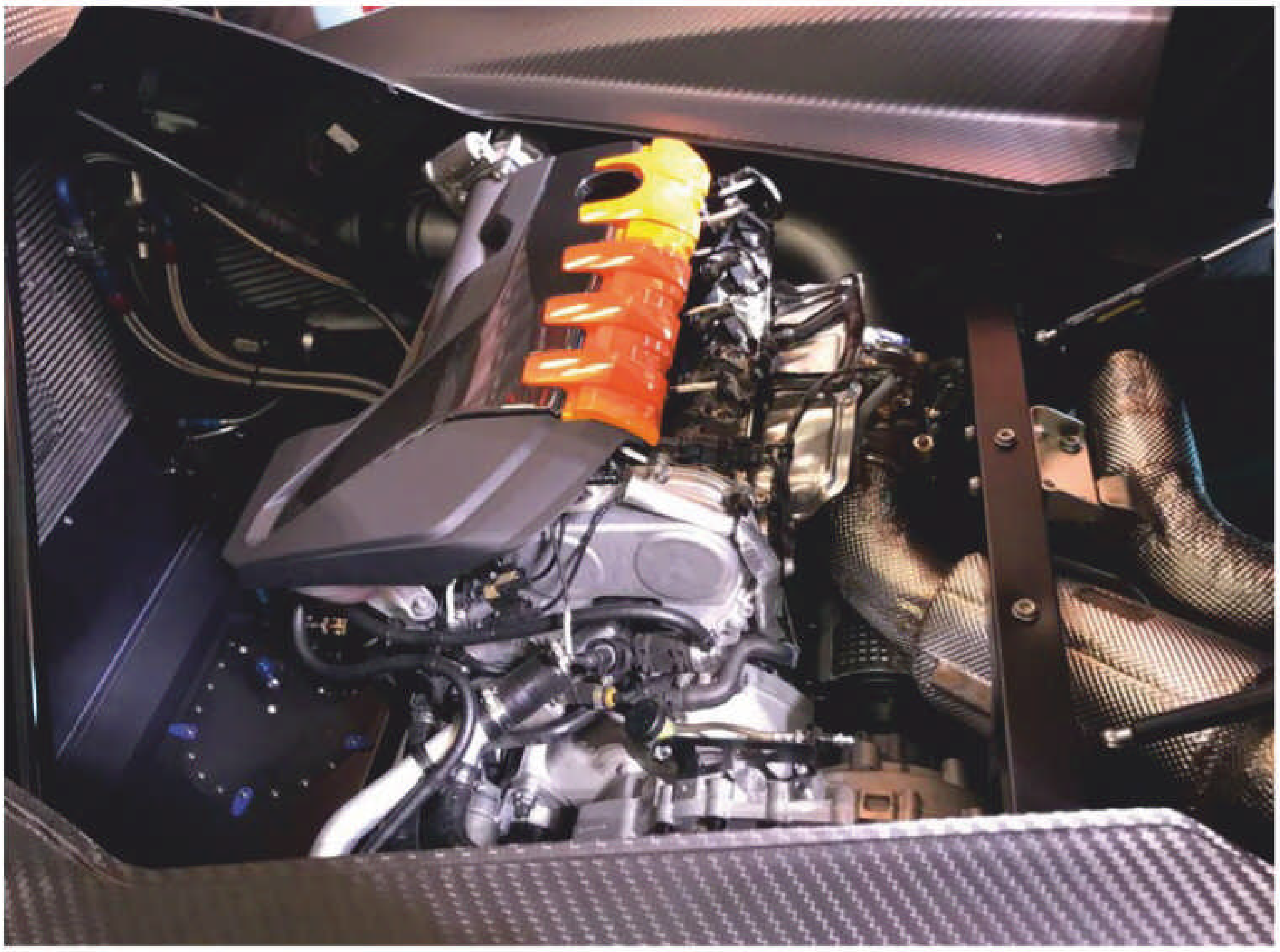
That work centred on producing a stable car at high speed. 'What we learned from GT4 is, if you don't have the top speed, [amateurs] don't want the car,' said Reiter at the launch

If you want to triple the downforce, you can simply open the aero

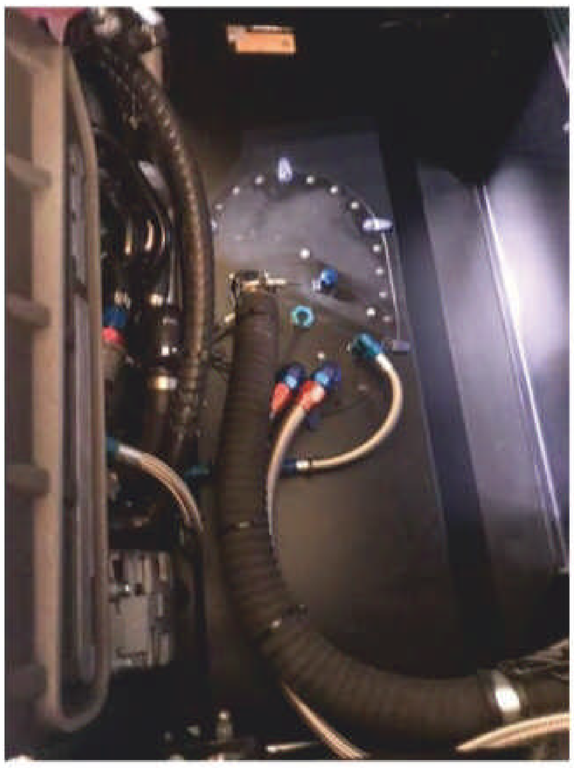
Hans Reiter, Reiter Engineering

Car has a huge aerodynamic window, with the option to double, or triple, available downforce through simple adjustments

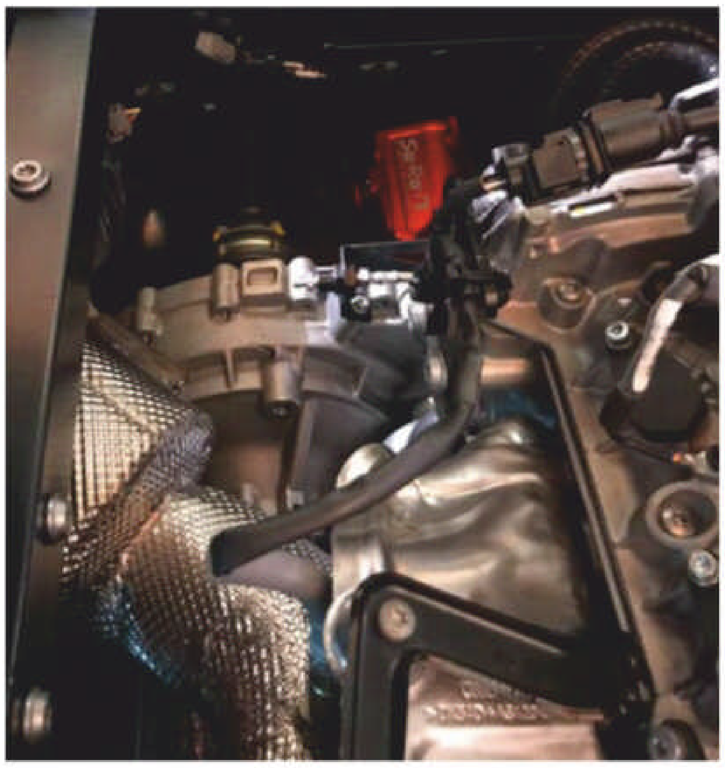
Suspension is independent double wishbone with Sachs coil spring / dampers all round, the rear is twin push rod-actuated



Engine is a five-cylinder, 2.5-litre Audi TFSi unit developed by Lehmann Motorentechnik to produce 591bhp at 7000rpm



Should you wish to race carrying two cases of beer…



Car features a six-speed sequential gearbox with paddle shift

of the car in Belgium at the end of October. 'In Red Bull Ring [during an ADAC race, a car was raced with development parts from the new KTM], going up the hill we were doing 257km/h, while the fastest GT3 was doing 242km/h. It is incredibly fast on the straight.'

Bang for buck

The whole car concept is supposed to be lightweight and simple, with a view to keeping costs down. Customers will be offered maximum bang for their buck, and the tactic seems to have worked. In the same way as GT3 was launched at the end of 2005, the non-professional drivers are looking for performance at reasonable cost.

'We picked up the 'phone and 20 cars were sold,' claims Reiter. 'GT2 will take off because we had the same situation in 2006 with GT3. We had rich people and they couldn't race anywhere. Now they are all gone. I don't see them here anymore. They haven't lost interest in racing, but they do not want to race manufacturers. You have to ban manufacturers and the silver drivers and have affordable cars like this one.

'Without coronavirus, I would say that GT2 would explode next year. The GT4 market is quite full, and the GT4 market is a mixture of junior drivers and [amateurs], and the [amateurs] will come to GT2 I think.'

A lot of effort has been made to drive down the base weight of the car to just over 1000kg, although in GT2 trim it will have to have more than 200kg of ballast added due to balance of performance.

Performance figures

The car features the Audi 2.5-litre, five-cylinder TFSI engine taken from the production range. In GTX trim producing around 373kW (500bhp), the intercooler is untouched compared to the production Audi unit, but the injection valves, wastegate, intake and exhaust system have all been adapted, as has the software to manage the engine. For the more powerful GT2 version, Reiter turned to Lehmann Motorentechnik for the development and the resultant performance figures, pre BoP, are 441kW (591bhp) at 7000rpm and a maximum torque level of 720Nm (531ft.lbs) available between a very useable 3500 and 5000rpm.

The engine bay is unusual in that the Audi engine does not sit as close to the centre of the car as possible. Instead, there is room for two cases of beer behind the driver compartment (the Germans proudly tested this before releasing the design) and the engine is slung out over the rear wheels. In terms of weight distribution tactics this seems to be a mistake, but Reiter says the balance of weight is similar to the Lamborghini Gallardo.

'The wheel loads on the back are less than a Gallardo because [the car] is so much less

A lot of effort has been made to drive down the base weight of the car to just over 1000kg

weight,' says Reiter. 'It has 120-150kg less than a Gallardo. Because I have less weight in the car, if I go to GT2 I can add 200kg to the front and have an even better weight distribution than a mid-engine car!

'The first thing was to make it light, not by money, but by concept. You have the Gordon Murray car that is also light, but it is expensive. We had the option to be expensive, but we chose to do it by concept instead. The gearbox has no crown wheel pinion, because it is built this way. As a result, it is only 52kg, and the Lamborghini gearbox is 94kg.

Concept light

'The first thing was to look at making things super light, and then at weight distribution. Because the engine is [rearwards], look how short the exhaust is. It is light by concept, and then we figured out the weight distribution.'

The choice of engine was not what Reiter originally had in mind when he first looked at the car. He wanted a V8, but KTM overruled him in favour of a production-based Audi unit that would not only produce the power, but would be reliable, even in a racing application.

A replacement engine is not expected to cost more than €20,000 (approx. $23,450) and the base engine can be purchased from any production Audi dealership.

It is not the only aspect of the car that comes from the Audi range. The electronic power steering system has also been developed by the German manufacturer. 'The problem with road car systems is that you struggle [to get] access, but we have all the support from them and it is suddenly cheap,' admits Reiter. 'If you don't have access [to the production-developed parts direct from the factory] then you are dead.'

What is unusual in the car is the electronic gearshift mechanism, about which Reiter is justifiably proud as it has been developed by his company, although he admits there is still a lot of work to do yet in order to understand its full potential. While other categories such as LMP already use such technology, it has been developed with manufacturer money, which Reiter didn't have.

'The gearshift we developed on our own,' he confirms. 'I think in five years every GT car will have electric shift. It is so much better, and it has so many more options for the future, but at the moment it is so expensive that no one is even considering it.

'There is a lot of investment in its development. We have been working on it for one and a half years already and have only scratched the surface of what it can do. In LMP racing they [are so advanced that they can] calculate the gaps between gears but for us, we are just happy that it shifts!'

Retaining control

The car is running endurance calipers, discs and pads from AP, which will help bring down the servicing costs, but the ABS system, provided by Continental, is the same as Reiter uses on the Gallardos. Again, it is able to be tuned according to driver ability and weather conditions. While this system is reliable, is Reiter not opening up too much variance in the set-up ability of the car that it becomes too complicated for the average driver?

If we haven't made a mistake, you don't need to touch it

Hans Reiter

'We would not give customers access to [programme] it,' he says. 'You have one engine map. You select what boost pressure you are supposed to run, and we are developing something that allows the mapping to self-learn. Same for the shift system. We will develop it, but the customer will only see if it is okay, not programme it.

'For the ABS, you have switches. Do I want more, or less? And that's the same with traction control. We will not have too much variation. For the mechanics, it is not so much. This is service free. If we haven't made a mistake, you don't need to touch it.'

With all the main parts of the car already developed, it should be reliable from the start, and Reiter says the GTX car has already managed to do the distance of two 24-hour races without any mechanical issues. 'I don't know where the end is, but in 500bhp configuration it is really robust. We didn't find a weakness,' he says proudly.

With GT3 entering a new phase in 2022 with new manufacturer-led, FIA-owned regulations, GT2 is there as an alternative option. Manufacturers have set up customer service departments, and GT2 fits nicely with this as a new revenue stream within an existing structure. Although GT3 cars are currently headed more towards manufacturer and professional drivers, Reiter still sees a future for the class alongside his new GT2.

The only questions now are how many manufacturers will jump on the GT2 gravy train, and when will they need to do so?

TECH SPEC: KTM GT2

Body style:	Mid-engined racecar		
Chassis:	Carbon composite monocoque; transverse engine; rear-wheel drive; independent suspension		
Motor:			
Make	Audi 2.5 TFSI		
Type	Turbocharged, five-cylinder petrol with combined intake manifold / direct fuel injection		
Capacity	2480cc		
Max power	Approx. 600bhp (441kW) at 7000rpm (using 98RON unleaded petrol)		
Max torque	720Nm from 3500-5000rpm		
Transmission:	Sequential six-speed gearbox with paddle shift, mechanical locking differential		
Suspension:			
Front:	Independent, double wishbones with twin push rod-operated Sachs concentric and adjustable coil spring / damper units mounted on top of the monocoque; anti-roll bar		
Rear:	Independent double wishbones with Sachs concentric and adjustable coil spring / damper units; anti-roll bar		
Steering:			
System	Electric PAS		
Brakes:			
System	Hydraulic dual-circuit with adjustable ABS		
Front:	AP Racing 378mm ventilated discs; six-piston calipers		
Rear:	AP Racing 355mm ventilated discs; four-piston calipers		
Wheels and tyres:			
Front:	18 x 11in magnesium with 30/65-18 Michelin slicks		
Rear:	18 x 12.5in magnesium with 37/71-18 Michelin slicks		
Dimensions:			
Length	4626mm	**Width**	2040mm
Height	1140mm	**Wheelbase**	2850mm
Track front	1752mm	**Track rear**	1710mm
Weights and capacities:			
Dry weight	1048kg (SRO BoP 1250kg)		
Front / rear split	42 / 58 per cent (static)		
Fuel tank volume	120l FT3 safety tank		
Lateral acceleration:			
Slicks	> 2.0g		
Maximum speed:			
Vmax:	> 300km/h		

Both the GTX track day car (shown) and GT2 use a 'jetfighter canopy' for access, with an opening side window in case of inversion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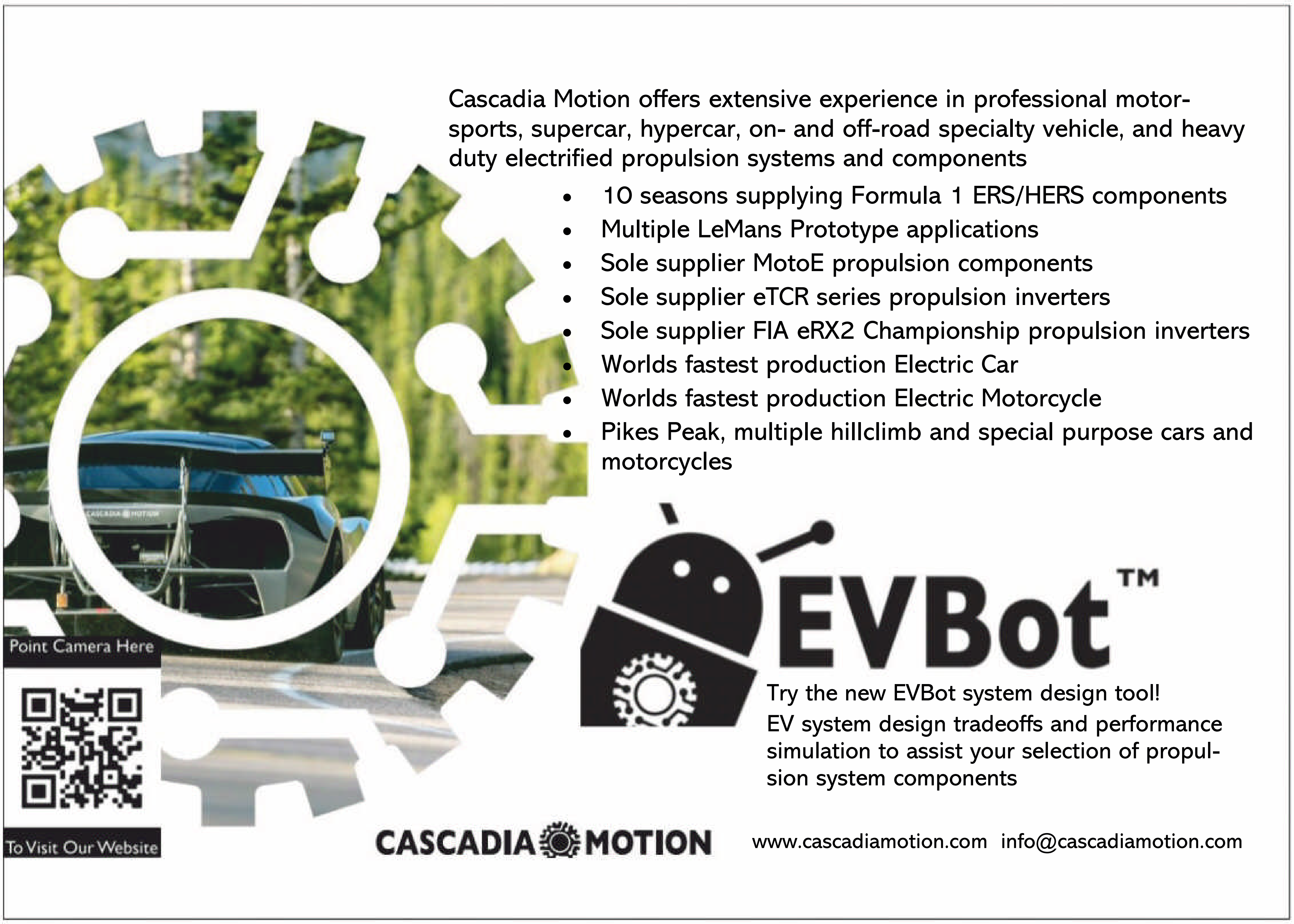
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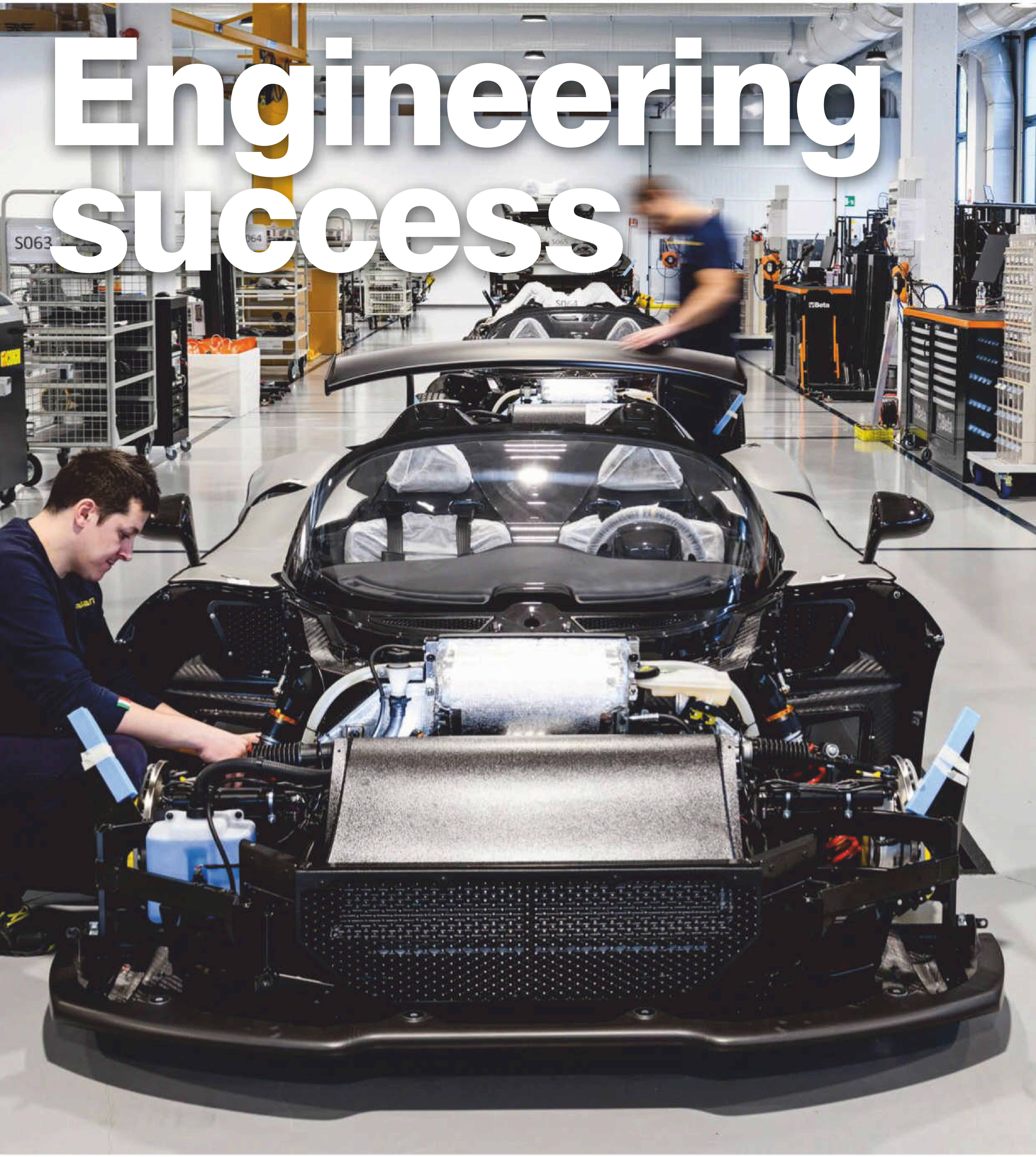
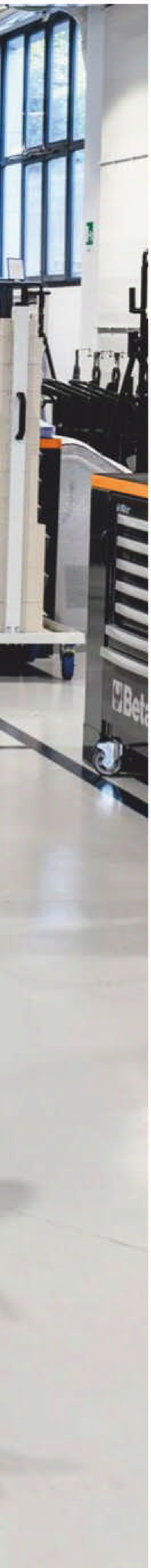


Dallara Automobili is a major player in global motorsport. *Racecar* spends an hour discussing the present and future with the company's founding father

By DIETER RENCKEN



Travel from Milan to Modena, both famous for their contributions to automotive history, and roughly midway along the two-hour journey the E45 bypasses Parma. Head due west along rural roads for 40 minutes and the sand-coloured Castello di Varano De' Melegari signifies your arrival in the small village (population 2500) of the same name.

Renowned for its imposing 10th century castle, Varano De' Melegari is better known in motorsport circles as home to the world's largest producer of racecars, Dallara, founded by the region's most famous engineer, Gian Paolo Dallara, born locally in 1936.

In 1959, Dallara graduated in aeronautical engineering at the Milano Politecnico University, then immediately joined Ferrari and worked his way through various technical departments, before moving to Maserati to join its sportscar racing operation full time.

Next stop was the nascent Lamborghini company, where Dallara formed part of the 350 GT design team before formulating the running gear for the groundbreaking, mid-engined Miura, generally accepted as the world's first supercar. Thereafter, he accepted an appointment at De Tomaso, a brief which included designing the company's Formula 1 car raced by the Frank Williams team.

In 1972, the ambitious engineer returned to Varano to found Dallara Automobili da Competizione in a small building beside the family home, where he lives to this day. The company expanded over the following five decades into a newer complex situated 'just up the road', but the original facility continues to produce cars of a more practical nature. The sublime Stradale road-going supercar is built almost in Dallara's back garden.

Core markets

Excluding Stradale (originally Gian Paolo's 80th birthday present to himself and the company), Dallara has capacity to build 200 competition cars in a 12-month period, although typically produces 70 units per annum, with the ebb and flow dictated by regulation changes in core markets, namely Formula 2 / 3 and, of course, IndyCar, which exclusively uses Dallara chassis.

Formula E, LMP2 and various national F3 championships, in which the company originally made its name, are valuable contributors, as is the Haas F1 programme, which Dallara expects will be extended, and for which the company designs and produces the bulk of listed parts and those not sourced from Ferrari. It also fulfils contracts such as monocoques and other hi-tech components to the likes of Audi, Bugatti, Ferrari, Lamborghini and Maserati.

Before the Haas co-operation came to fruition in 2016, Dallara had provided services to an array of F1 projects, both as Dallara – scoring two podiums – and consultant and supplier of technical services to Honda's late '90's in-house project, which set fearsomely fast lap times before being inexplicably aborted (a common thread in Honda's F1 history). The constructor also conducted subsequent collaborations with Jordan / Midland and Campos / HRT.

Factor in simulator work, drawing on both NASA and automotive principles, as befits an automotive company founded by an aeronautics engineer, a standalone IndyCar factory in Indianapolis, plus numerous wind tunnel contracts and direct access to nearby Autodromo Ricardo Paletti, and clearly Dallara Automobili is a major player in the global motorsport space.

Backing that up, every current F1 driver has won with Dallara during his formative years, while Dallara technologies and / or products have been at the forefront of all major racing series in recent years, plus plenty of lesser-known ones as well. Talk sportscar racing, and Lancia entrusted its world championship programme to Dallara. Mention DTM, and Dallara contributed massively to Audi's effort. Ferrari's 333 SP IMSA sportscar? Again, Dallara.

Times and technologies have changed dramatically during this period, with arguably the biggest single development being an almost universal switch from proprietary chassis to one-make series. It could be argued that Dallara's domination of F3 and IndyCar meant no other constructor had a look in anyway, effectively reducing grids to one make, but the concept was embraced with a vengeance by series promoters.

At a stroke of a pen, the competition was no longer primarily about performance but price and, while the company may well have floundered at the elimination of its key advantage – namely producing the fastest cars in its contested categories – Dallara instead flourished commercially, as long-term F2, F3 and IndyCar contracts attest.

Dallara has capacity to build 200 competition cars in a 12-month period

The company is still managed today by its founder, working in conjunction with CEO / shareholder, Andrea Pontremoli, who hails from the nearby village of Bardi and joined the company from a senior executive position with IBM Italia in 2007. 'My job is to ensure the essence of Dallara is enhanced,' he says.

Challenges ahead

Gian Paolo Dallara and I had met once before, albeit briefly, but on that occasion only had time for cursory questions, so I was delighted when he agreed to set aside time for a full interview for *Racecar Engineering*.

After greetings and mutual agreement to remove masks but maintain social distancing, I pose the opener: What is the biggest challenge facing racecar manufacturers?

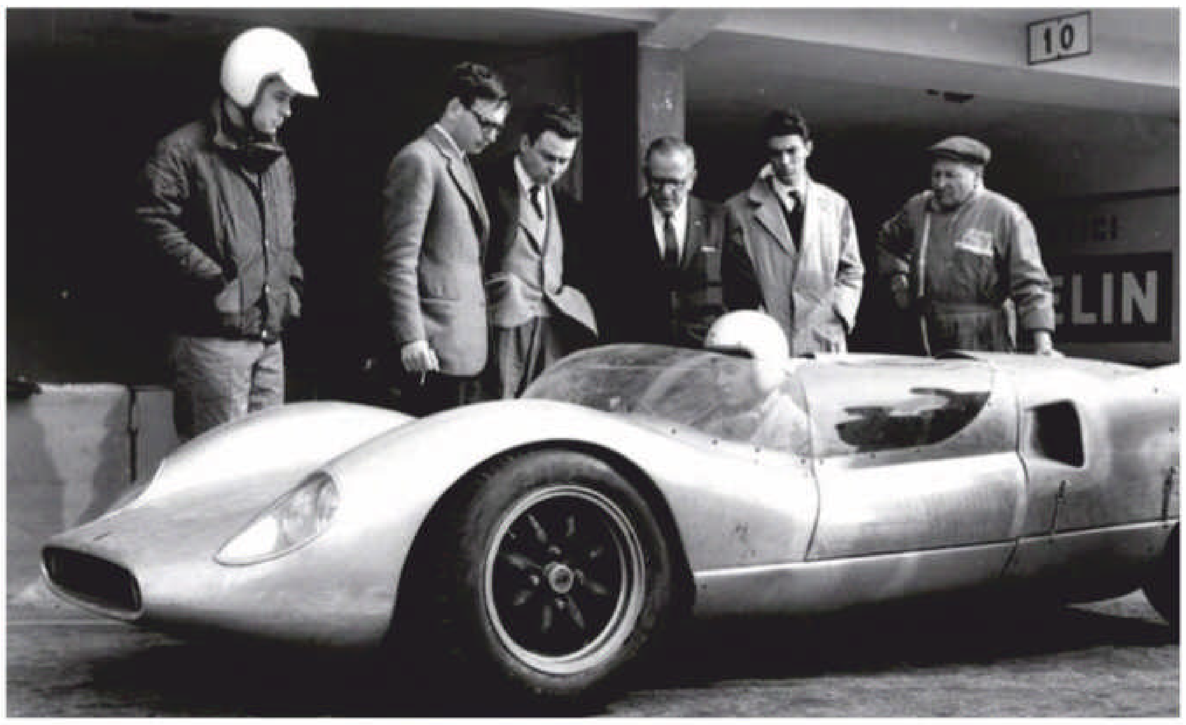
'I believe that like in Formula 1, they are trying to reduce the cost of racing, in every kind of racing,' he says slowly and deliberately. 'So we have to try to make the car with components that have a longer life. The car has to last longer, [but] has to have the performance in terms of lap time, but with a less expensive solution.

'I believe that in the future all the racing world will need to be less expensive.'

I note that prior to answering, he looks out of the window at the museum as though drawing inspiration from the past before addressing the present and future.

Where does the optimum balance lie between performance, weight and cost?

'Of course, if you want a car to perform very well, you need a car that's very light.



A young Dallara (second left), studies a Cooper Maserati 2, along with Bruce McLaren and Roger Penske

But compare the difference between alloy and steel. Six kilos is maybe something like €10,000 [approx. $11,900]. So, if you want to save the last 10kg, it could cost you €20,000 [approx. $23,800], and [you] have to use different materials and more sophisticated design to achieve that.'

He then goes back in time, using ground effects cars with flat floors as an example. The powers that be decided the cars were too fast, he says, so mandated flat floors. The net effect was that engineers clawed back lap time through increasingly exotic materials and complex wing designs. The inference is cars would have been faster and cheaper without the interference of regulators.

'It is possible to think how to make a faster car less expensive…' dropping his voice slightly as he continues, '[but] we have never to [sacrifice] in terms of safety.'

In a brief interlude, he makes reference to the dismal safety standards of 1950's and '60's cars, and the total absence of circuit safety.

'Then came [US safety crusader] Ralph Nader, who wrote a book [*Unsafe at any Speed*] and we thought why? But now we know he was right. Now in every technical committee, the Automobile Club of Italy and also the single seater group of the [FIA], every time someone suggests a solution in the direction of safety, no one is saying no.'

I delicately broach the Piers Courage accident, in which the Briton perished in Zandvoort in 1970 after the suspension on his Williams-run De Tomaso broke, pitching it into a barrier where it burst into flames, in turn igniting magnesium chassis members.

Dallara's eyes cloud over momentarily, then he repeats the word 'Yes' six times before a quiet 'It is so. You can spare cost everywhere, but not ever in safety.'

It is clear that tragedy had a profound effect on his approach to racecar design, leading me to a logical follow-up: Should racecar engineers spend more time, money and effort on safety than on performance?

The answer is affirmative, but Dallara believes impetus needs to come from authorities to prevent a manufacturer grabbing unfair performance advantages: 'I believe that if you make a car that is a little safer, but it costs a lot more than your competitors, maybe you will not [sell] it.'

With the move to single-make series, there is obviously less scope for racecar engineers to express their inherent creativity, so does he think motorsport is in danger of trading innovation for commercialism?

Think young

Dallara first points out that not all series are one make, and lists various manufacturers across the globe, but concedes individual opportunities have reduced over time. However, new fields and technologies provide opportunities that did not previously exist. Then follows that up with a curved ball: 'They say the driver should not be assisted. That there should be no ABS, no traction control, no servo-assisted steering, no active suspension. I believe there should be more freedom to 'think young'. This is something that will change in future.'

At which point he takes the opportunity to introduce the masters degree course in automotive engineering offered by the Motorvehicle University of Emilia Romagna (see box out on p46). MUNER courses include advanced automotive electronics, race / high-performance car design, advanced powertrain design and more. Details can be found at www.motorvehicleuniversity.com.

Dallara then points enthusiastically to the enormous strides being taken in aerodynamic testing as proof of additional opportunities open to today's engineers, listing advances such as 'moving roads', yaw and pitch and wind tunnel tyres, even before computational fluid dynamics entered the equation. 'It's a very, very important activity,' he says.

Add in physical verification via on-car data logging, and it is clear that while the base may have narrowed, the scope for engineers has broadened exponentially.

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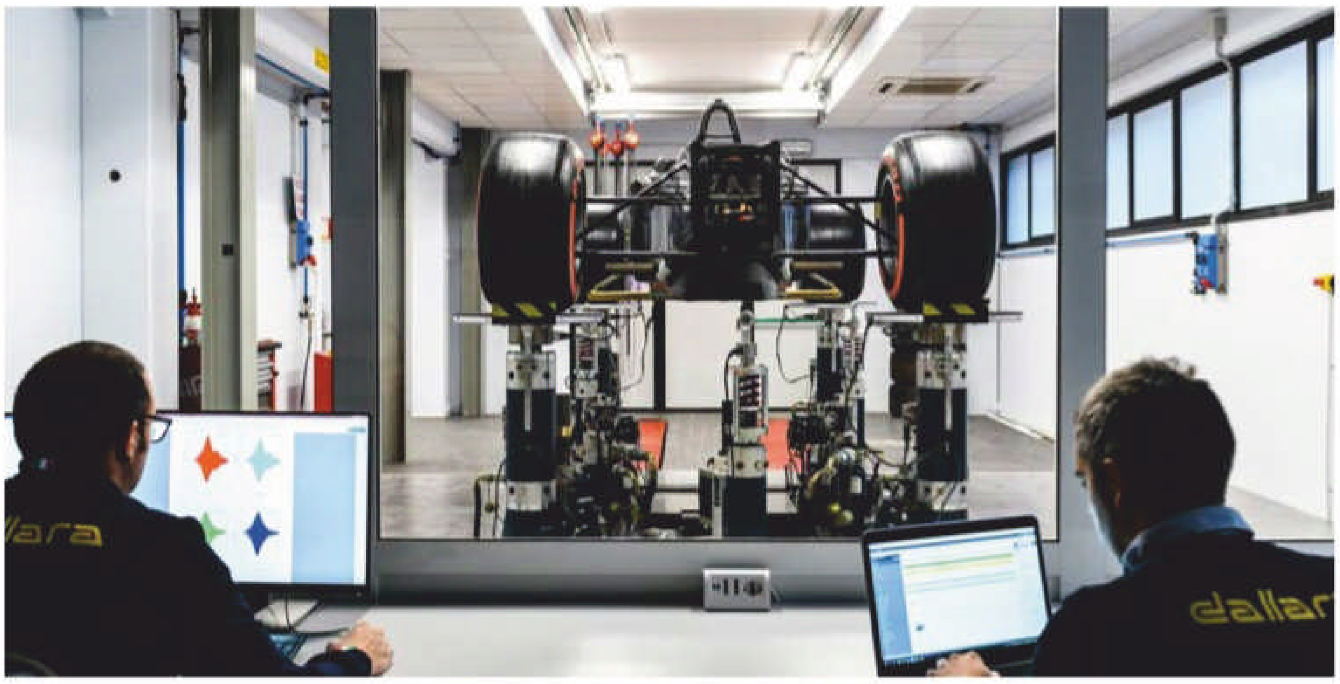
With a background in aeronautics, it's no surprise Dallara places a great deal of emphasis on aerodynamics



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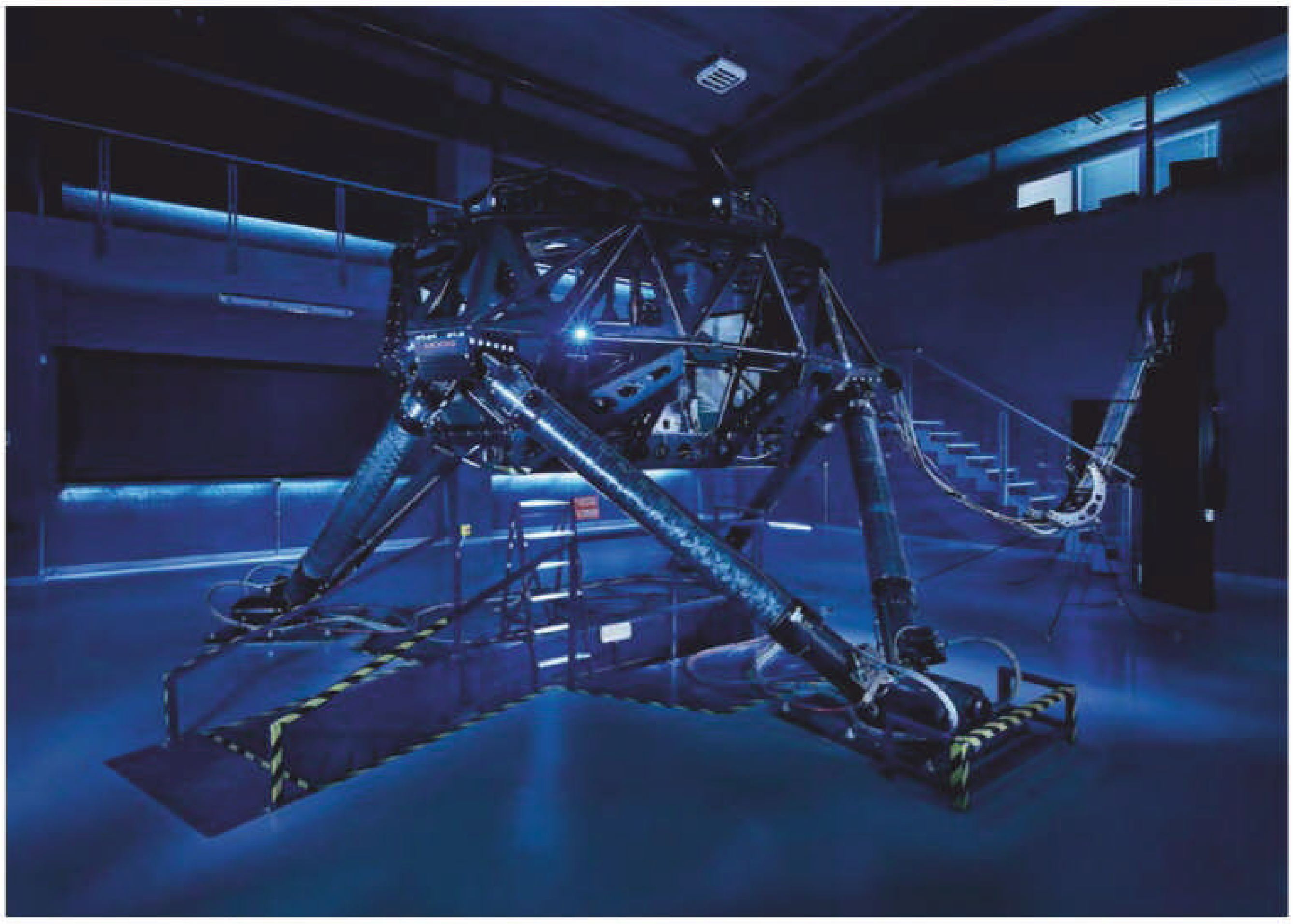
The facility also includes dynamic test rigs, all of which will be made available to Academy students

I think these [current] rules are pushing engineers to learn how to [manage] without real testing, physically. This is the way [forward]



Fabrizio Piscopo

We imagine a driving simulator module would be a popular part of the masters degree in automotive engineering

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Scale models for wind tunnel testing under construction at the Dallara facility

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The Dallara composites department is amongst the most advanced in the world, holding contracts with all major race series

So how, in his opinion, can Formula 1 get away with little or no testing, and is that going to be the way forward?

There is a pause, before Dallara references 'virtual garages', which collect data every time a car runs. 'They are right to reduce costs, of course, and I think these rules are pushing engineers to learn how to [manage] without real testing, physically. This is the way [forward].'

Which neatly introduces the advances made in data logging into the conversation.

Continuous flow

'There was the arrival of computing systems, then came data logging systems, but you had to [download] when the car stopped. Later, the point arrived when the [car] was passing, and then later came 20 channels and a continuous flow of everything in real time.

'Now you can transfer an area where they can simulate and check, and they try to understand why. You can have one driver at the wheel, and another trying to make the same results in some other part of the world. All in 20 years of evolution.'

Dallara's unwavering belief that engineers face more opportunities than ever before is well made, but with moves afoot to ban virtual garages on cost grounds, is simulation not more expensive than testing?

'No,' he replies emphatically. 'Testing is more expensive because you need more people, and you need more materials because components have a life[span].'

The same philosophy applies to a 'tyre war'. While Dallara the engineer favours open competition, Dallara the businessman is more cautious, saying, 'that's another [element] of competition that increases costs.'

Against these backgrounds, what is his take on F1's 2022 'new era' regulations? More particularly, the imminent imposition of favour budget caps in what had previously been an open spend category?

'I believe they are moving in that direction to reduce costs in every area, including aerodynamics and development, and that [F1] could not afford to continue [as it was].

So, budget caps, does he agree with them?

'We have to agree,' he smiles wryly, before qualifying his philosophy: 'If they bring closer competition, [yes]. Normally you have two, three teams with more money, we need more races like [the Italian Grand Prix, unexpectedly won by Pierre Gasly and AlphaTauri].'

Budget caps will probably force Ferrari into diversification, with IndyCar and the top WEC / IMSA category its most likely targets. If so, would Dallara wish to be actively involved, as it had been with the glorious 333SP?

'[The moves] could happen. I read recently that [Ferrari president] Louis Camilleri said they are interested. That is a good signal. There will be tremendous growth, it will be important for the series.

'It would be very interesting for us, but I think at the moment they are thinking let us see what is going on.'

Future technology

Looking to the future, Dallara provides carbon fibre / aluminum chassis and survival cells for Formula E, so what is his take on electrification for both road and track?

'It will happen. I'm just not sure *how* it will happen,' comes the reply, adding it could either be via battery energy storage or hydrogen fuel cell. Which neatly leads to the question, can hydrogen be safely stored?

Dallara has no doubts the technologies exist to safely contain the gas at 300bar, but believes it will first be used in aircraft, and then trickle down to automotive, citing recent studies undertaken by his *alma mater*.

Equally, he believes autonomous cars will become a way of life in future, but only for commuter transport. He thinks cars and motorcycles as we know them will still be used for pleasurable pursuits, for when personal mobility and freedom is sought. 'But if I need to take a car for business to Milano, I would not enjoy driving.'

Imagine an autonomous car racing with a car driven by remote and a car driven by a driver. Who would be the best?

Then Dallara adds an intriguing twist: 'It would be very, very interesting in the future… imagine an autonomous car racing with a car driven by remote and a car driven by a driver. Who would be the best?'

Finally, I ask what conflicts exist within the two Gian Paolo Dallaras, the engineering purist and the astute businessman who bears responsibility for over 600 staff, plus scores of contractors and the personnel employed by a massive supply chain?

'In my experience, I prefer the freedom [to engineer], but as a businessman I need to be in a condition to not lose money. And if I lose this year, I must ensure I have the chance to recover next year or I close.'

Dallara's 50-year record in a highly competitive business with a survival rate of less than 10 per cent suggests he and Andrea Pontremoli have struck the perfect balance between creativity and profitability.

Dallara Academy

From the mind of Alfonso Femia, the Dallara museum and Academy building is a masterpiece of design, much like the racecars it houses and the roadgoing Stradale parked outside

Fabrizio Piscopo

Alessandro Not

Within the boundaries of Dallara's main complex, beneath the museum that contains the first car to bear the Dallara name up to the latest Haas F1 racer, is the Dallara Academy, an 'edutainment' centre that offers laboratories and simulation tools for young engineers to experiment with the physics of racecar engineering, with particular reference to the science of aerodynamics.

Opened in 2018 by the local mayor and Alex Zanardi, the visually arresting building also houses the second year MUNER faculty, which offers a masters degree in automotive engineering, in conjunction with local learning establishments.

Promoted by the region of Emilia Romagna, the universities of Bologna, Parma, Ferrara and Modena participate in the course, as do hi-tech and automotive companies in Italy's Motor Valley, including such as Ferrari, Maserati, Lamborghini, [AlphaTauri], Ducati, Dallara, Magneti Marelli and Haas. In terms of EU grants, MUNER is open to students from across the globe.

'We want to invest in the growth of knowledge within [Italy's] Motor Valley,' said company founder, Gian Paolo Dallara, during the opening ceremony. 'Youngsters have all [facilities] available to them: Dallara provides the wind tunnel, the driving simulator, the carbon research centre and the state-of-the-art facilities that no university could afford to purchase and make available. Also, a part of the teaching will be carried out by our managers.'

The Academy building also houses a conference centre open to companies in the region, whether automotive-linked or not. The idea is to provide a fusion of technology and commerce – the key elements that enabled Dallara to survive in the racecar construction business for almost 50 years.

The museum exhibits include a breathtaking array of racecars, all either built by or developed by Dallara

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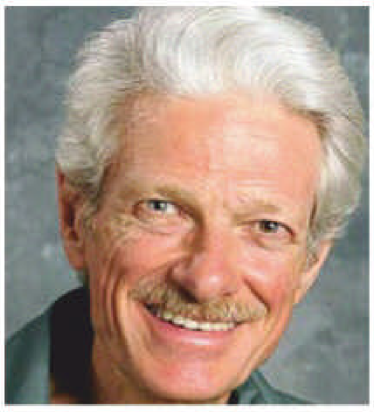


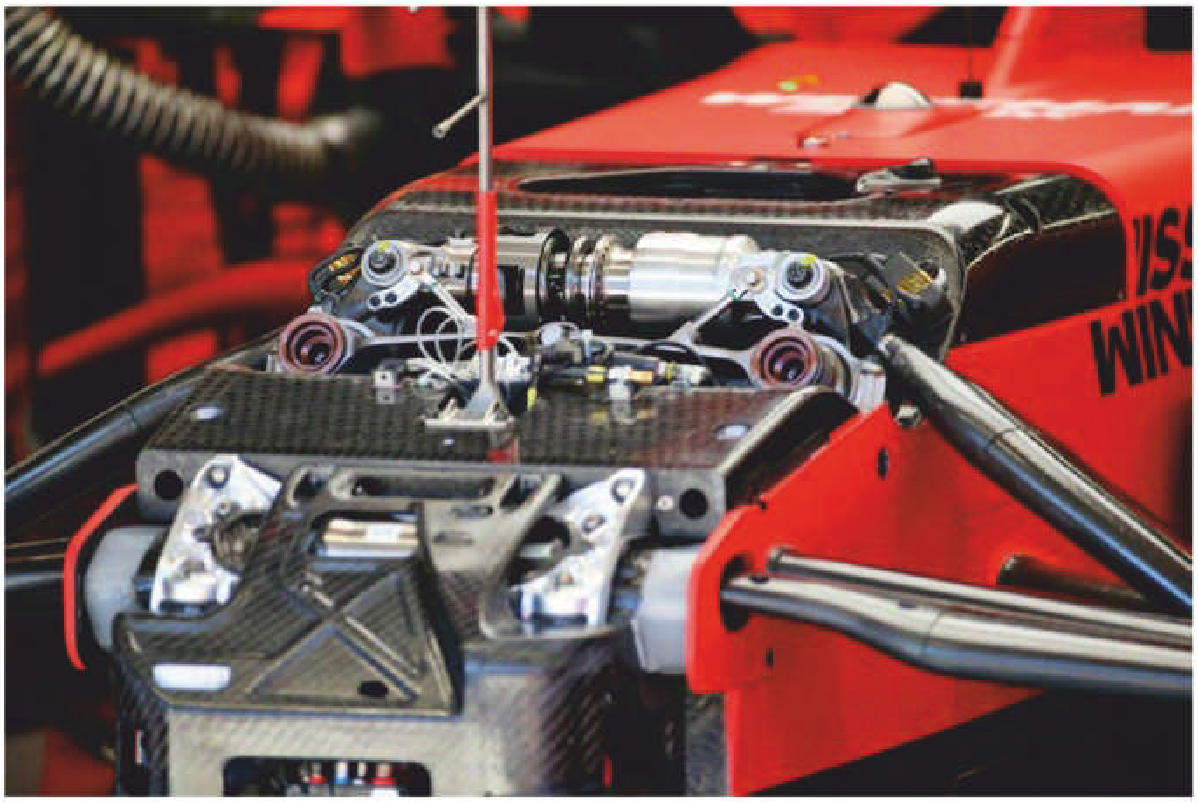
Rate my bar

Stresses and structural efficiency in anti-roll bars

By MARK ORTIZ

Q We race off-road trucks that have upwards of 10 inches of wheel travel. We have trouble getting adequate rate out of our anti-roll bars and still having them last. If we make them thin and soft they'll last, but they don't do much. If we make them fatter, they get stressed past the yield point and either break or take a permanent twist. Is there anything we can do to improve this situation?

One idea that has been suggested is to have the drop link act near the middle of a trailing arm. Would that help?



It is relatively easy to tune anti-roll bar or torsion bar rate and stress, the limitation is often one of packaging

THE CONSULTANT

A There are ways to reduce stress levels in either an anti-roll bar or a torsion bar that holds the vehicle up, but what you can actually do on an existing vehicle comes down to packaging. Assuming you don't want to give up rate, here are your options:

1. Make the bar longer and fatter.
2. Make the arm length greater, and make the bar fatter.
3. Make the bar act through another arm, or linkage, that reduces the bar-to-wheel motion ratio, and make the bar fatter.
4. Make the bar solid, not hollow (assuming it isn't already).
5. Use multiple bars, located either in series or in parallel.

The second and third of these do basically the same thing. They reduce the bar-to-wheel motion ratio, understood as degrees of twist per unit of wheel movement. This requires the bar to be fatter, which increases stress per unit of twist, but we still come out with lower stresses for the same rate.

At arm's length

This results from the fact that, for the same rate at the wheel, torque on the bar per unit of wheel travel goes up with the square of the effective arm length, but the stiffness of the bar goes up with the fourth power of the diameter and the strength of the bar goes up with the cube of the diameter.

This is the formula for rate of a torsion bar:

$$s = (.098\ d^4\ G) / (R^2\ L)$$

where,
s = rate at the arm end, lb/in
d = diameter of the bar, or portion of the unit that twists, inches
G = shear modulus of elasticity, lb/in^2
R = perpendicular length of lever arm, inches
L = bar length, inches

With SI units, the basic form of the equation is the same. Only the .098 coefficient changes. For a hollow bar, the d4 term is replaced by (do4 – di4), do and di being outer and inner diameters respectively.

This is the formula for simple shear stress in a torsion bar:

$$\tau = T / (.196\ d^3)$$

where,
τ = outer fibre simple shear stress, lb/in^2
T = torsional moment, lb/in
d = bar diameter, inches

Again, with SI units the form of the equation stays the same, but the coefficient changes. For a hollow bar, d^3 is replaced by $(d_o^4 – d_i^4) / d_o$.

To take an arithmetically simple case, if we double the effective arm length, the bar has to exert four times the torsional force per unit of twist, but only sees half the degrees of twist per inch of wheel movement. The rate ratio is the square of the motion ratio, as with any spring. This requires the bar to be fatter by a factor of the square root of two, or just over 40 per cent bigger in diameter.

But torsional stress for a given torque varies inversely with the cube of the diameter. That fatter bar can therefore withstand the square root of two cubed, or $2^{3/2} = 2.83$ times the torque without reaching its yield point, and we're only applying two times the torque per unit of wheel movement. The bar can withstand $\sqrt{2} = 1.41$ times the wheel travel without permanently deforming, and it sees only $1/\sqrt{2} = .707$ times the stress per unit of wheel travel.

So, one way to get a desired rate with lower bar stress is to ensure the bar twists less per inch of roll or warp displacement, and thicken the bar accordingly.

One way to get a desired rate with lower bar stress is to ensure the bar twists less per inch of roll or warp displacement

Stabilising Jaguar-style IRS with a Watt linkage?

Q I wonder, if you have a Watt link instead of a four link to handle acceleration forces, do you calculate anti-squat in the same manner as with a four link?

Oh, I forgot one important piece of information. The vertical link is not welded to the axle, it is linked at its centre as a normal Watt link for conventional lateral forces.

Let's say it is mounted on the rear upright, the differential is mounted on the car itself, we have live driveshafts with CV joints and the rotating of the upright is handled by one lower arm, which will not twist.

THE CONSULTANT

A Is this an independent suspension, then?

You are considering a lower arm that cannot twist, as in an E-Type Jaguar, but allows fore and aft movement? I'm having trouble imagining that. I guess something like a second driveshaft, connected to the frame rather than the diff' carrier, would do that, but are you actually thinking of that?

And are you considering inboard rear brakes, or outboard?

The Jaguar design requires Cardan-style joints rather than CV joints, so I'll assume you meant that. In this case, the driveshafts serve as upper control arms, so they have to be fixed length. As originally designed, there are no longitudinal members at all and the lower arm is tasked with reacting large lateral, longitudinal and torsional loads.

When used with large tyres and with lots of power going through it, it tends to deflect, causing compliance steer.

To try to band-aid this problem, later Jaguar suspensions have a trailing link on each side. Unfortunately, the motion of this link conflicts with the motion of the control arm. The control arm's motion is a straight line in side view, while the trailing link swings in an arc in side view. In front or rear view, the control arm swings in an arc and the trailing link has to move laterally at its rear end to accommodate that. So in order to allow for this, later Jaguar suspensions had to have compliant rubber bushings at the ends of the trailing link, which reduces its effectiveness in stabilising the system. A Watt linkage would be a better solution, if properly designed, albeit not quite as simple.

Bind rage

However, the Watt linkage would have to provide vertical motion in side view in order to not create a bind. That would preclude having any anti-squat or anti-lift in the system.

With or without the Watt linkage, the suspension can have some anti-squat and anti-lift if the whole geometry is, as it were, tilted back in side view, so that the lower control arm's axes of rotation slope up at the front. The Watt linkage would likewise be rotated in side view so that the rocker would be inclined back at the top and the links would slope up toward the front at static condition.

With a beam axle, if packaging constraints limit arm length, one possibility would be to have the arms bent inboard so that the drop links act further in on the axle. Another option would be to have the bars act through rockers of some sort.

But what happens if we use an extremely short bar, acting well inboard on the axle, as used in some drag cars? If we cut the degrees of twist per unit of wheel movement in half, but also cut the bar length in half, the degrees of twist per inch of bar length remain unchanged, and the bar becomes twice as stiff for the same diameter. But it needs to be four times as stiff to give the same rate at the wheel, so it has to be thicker by a factor of the fourth root of two, or about 1.19. That means the stress increases.

Take the strain

One other way to look at this is to consider strain: deformation of the material per unit of size. Stress and strain are always directly proportional, for a given material. Strain in this case is how much a notional outer fibre of the bar has to deform, per unit of wheel motion. This depends on the degrees of twist per unit of bar length and the diameter of the bar. If, for the same rate, the degrees of twist per unit of bar length stay the same but the bar diameter has to increase, we know that implies an increase in stress.

Even when the bar is solid, it will be clear that the metal closest to the outer diameter is doing the lion's share of the work. Therefore, making a bar hollow is attractive, if the stresses don't get too high. However, a hollow bar is inescapably larger in outside diameter and therefore has greater outer fibre shear stress at any given amount of twist per unit of length.

A hollow bar is inescapably larger in outside diameter and therefore has greater outer fibre shear stress

We can have a bar of lighter weight for the same rate with a hollow bar, but only by reducing the amount of twist per unit of length. That means making the bar longer, or making the effective lever arm length greater.

When the stress does not reach the yield point, but starts getting close to it, we have a bar that will serve for a while but will have shorter service life.

It will be apparent that this is one of many situations in engineering where structural efficiency, packaging efficiency, simplicity, cost, and longevity all trade off against each other.

There is one other way to avoid excessive stress; just make the bar so stiff and strong that the vehicle will lift a wheel before the yield point is reached, even at maximum combined upward and lateral acceleration. But if the idea is to have a very soft, long-travel suspension, we probably don't want that.

If I were designing an off-road suspension, and the rules allowed me a free hand, I would strongly consider using both diagonal anti-roll / anti-pitch bars and longitudinal anti-roll / anti-heave bars, rather than conventional anti-roll bars, which are really anti-roll / anti-warp bars. That would allow very long bars and also give a warp-soft suspension, which is valuable in any vehicle, but especially so in an off-road application.

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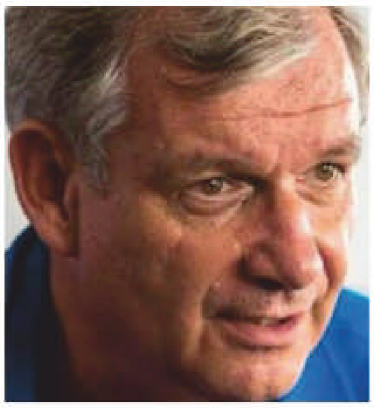


Spring brake

Understanding damping ratios and the notion of critical damping

By **CLAUDE ROUELLE**

Racecar suspension is a complex science, and requires much more than just an understanding of the dampers, but getting to grips with them is a good place to start

'The damper is the brake of the spring.' In this article we will review that theory, as well as the pros and cons of some oversimplified quarter-car simulation.

If you would put a mass on a spring with no damper and push the mass down by 60mm (as seen on the green trace in **Figure 1**), then release your force, the mass will oscillate indefinitely. We should say *nearly* indefinitely because ultimately the movement will stop, mainly due to the spring material internal resistance, but also because of air friction. Note that in this example you allow the spring to work in tension and move not only down but also up by 60mm. As we will see later that is not the case in most car suspension.

The mass position, as a function of time, can be described by a sinusoid called harmonic motion. The equations are as follow:
$z=Z_0 e^{(-\zeta\omega_n t)} \sin(\omega_D t+\varphi)$

With the undamped period being $\omega_N=\sqrt{K/m}$ in rad/sec and the undamped frequency $f=1/2\pi \sqrt{K/m}$ in Hertz (Hz)

The critical damping coefficient is $C_{crit}=2\sqrt{Km}$ in N/(m/sec)

The damping ratio is $\zeta=C/C_{crit}=C/(2\sqrt{Km})$, which is dimensionless.

The damped natural period is $\omega_D=\omega_N \sqrt{1-\zeta^2}$ in rad/sec, the damped frequency is $f=1/2\pi \sqrt{K/m} \sqrt{1-\zeta^2}$ in Hertz (Hz) with Z_0 being the initial amplitude (in metres), t the time in seconds, φ the phase difference (in radian), K the spring rate (in N/m), m the mass (in kg), and C the damping in N/(m/sec).

Be careful with the units here. Many make the mistake of forgetting to convert their spring stiffness from lb/ft into N/mm rather than Newton per metre. Likewise for the damper, that is in Newton per metre per second

Critical damping

That's it for the mathematical formulae, but what does it mean in practice? Let us start with the notion of critical damping and a simple example. You go in your garage and push down hard on your car bonnet / hood. The front part of the car's suspended mass goes down. Let it go, releasing the downward force, and the car will return to

Figure 1: Amplitude vs time for a simplified one degree of freedom (DOF) mass on a spring with different damping ratios

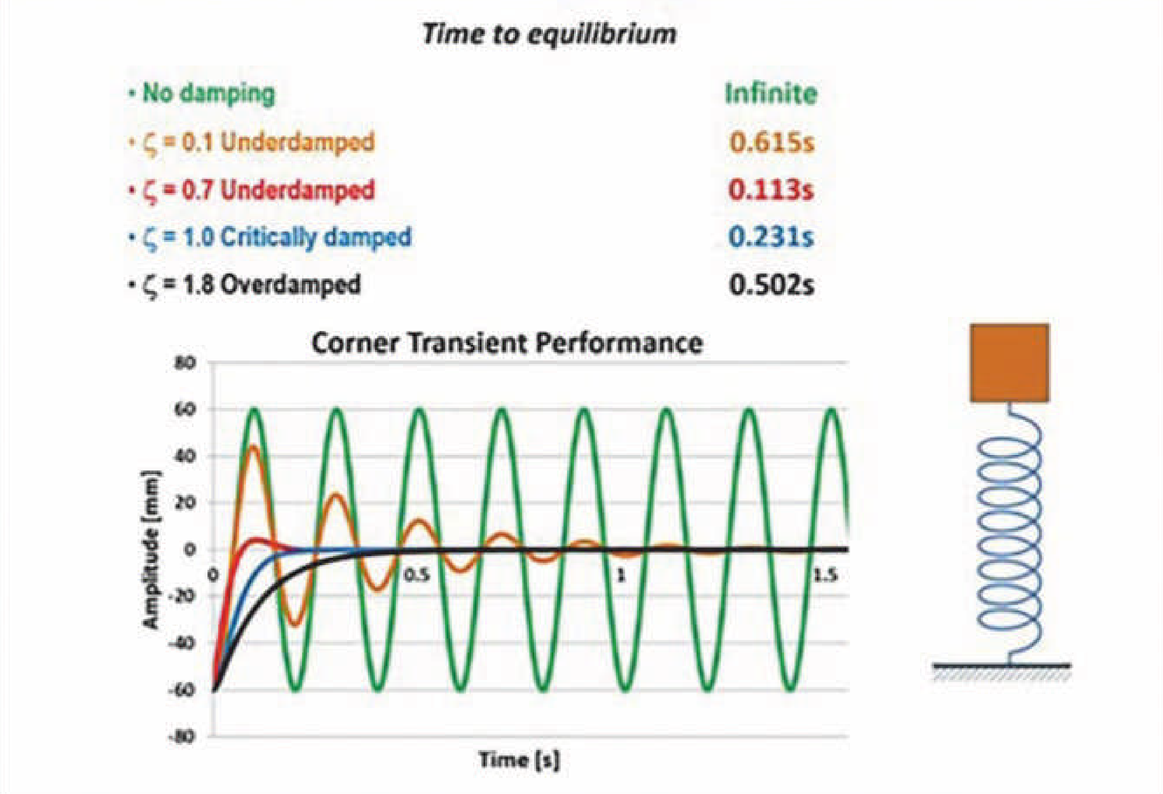
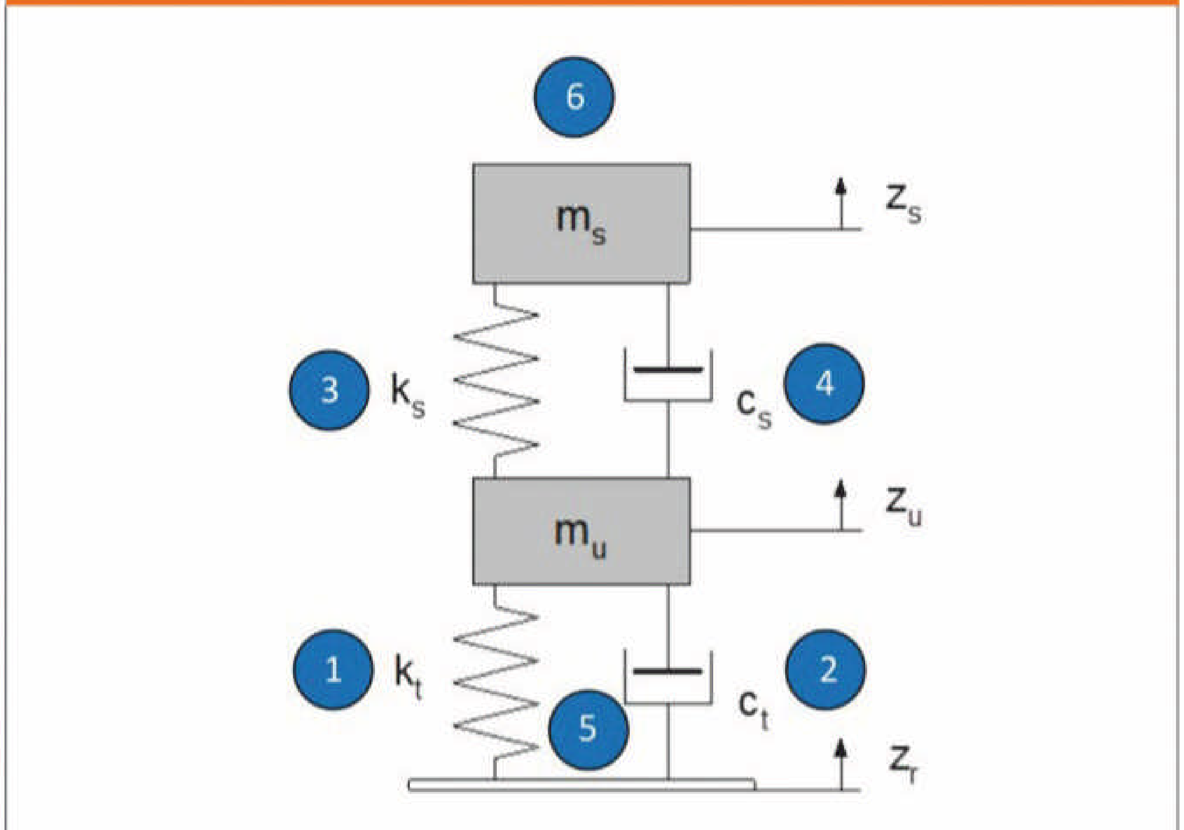


Figure 2: Two degree of freedom quarter-car model with suspended and non-suspended masses, tyre stiffness and damping, and suspension stiffness and damping



its initial position with a certain number of oscillations of different amplitudes. If the front suspension is critically damped, it will return to its initial state as quickly as possible without any overshoot. That is what $2\sqrt{Km}$ means, and it is represented by the blue trace in **Figure 1**. The damping ratio is one.

If your suspension is less damped, let us say at 10 or 20 per cent of the critical damping (damping ratio of 0.1 or 0.2) such as shown by the orange trace in **Figure 1**, it will take a while for the suspension to get back to its initial state.

Here's a simple illustration, and a trick for all racecar engineers. There are circuits where there is an annoying bump in one of the straights, usually above a tunnel passing under the racetrack. That bump did not exist in the first few years of the circuit's existence, but then with temperature variation and seasonal fluctuations the tarmac moves and creates the bump. As it is in a straight, approached at relatively constant speed, neither in a braking or acceleration zone, it has no influence on car performance and is just an annoyance for the driver.

Have a look at the damper's potentiometer signals: if it takes more than one, or even worse, more than two oscillations after that unique bump for the dampers to stabilise, you know your suspension is under damped. You do not know (yet) if the lack of damping is in compression or rebound, low or high speed, but at least you know you have insufficient damping.

The other specific case is the one of a critical damping of 0.7 (as shown by the red trace in **Figure 1**). That is the damping that will bring the mass back to its initial stage as quickly as possible, albeit with the 'cost' of an overshoot. If response to a steering input, or returning back as quickly as possible to a given ride height after a bump is the main target, usually a damping ratio of 0.7 is ideal.

We will not go into too much mathematics here, but you will notice that 0.7 is half of the square root of two. That is not a coincidence. It is worth noting that the mass goes back to its initial state in less than half of the time it takes with the critical damping.

The black trace in **Figure 1** with a damping ratio of 1.8 shows an over damped suspension. As we will see later, over damping does not make sense in terms of tyre mechanical grip consistency, but it could make sense in terms of aerodynamics, especially with cars requiring a constantly low ride height.

Minimum drag

Many years ago, that kind of damping was used in rear suspension rebound on Superspeedways in NASCAR. Aeromaps show that often a relatively high front ride height and an exceptionally low rear ride height, (of about 3mm) gives minimum drag. On tracks like Talladega and Daytona, minimum drag is a main target, more so than handling and downforce. However, the cars had to go through technical inspection with quite high static ride heights.

The trick was to use soft rear springs with just enough pre-load to maintain the rear part of the suspended mass at its legal static ride height for technical inspection. The springs used had low bump and exceptionally high rebound damper settings.

As soon as the car left the pit lane, the rear ride height went down under the effect of downforce, banking and every single little track bump. It went down until the rear springs were coil bound, reaching an exceptionally low rear ride height. So low in fact, and with such stiff suspension, that the suspended mass frequencies were so high they made the drivers' vision blurred. The cars were faster, but difficult to drive and unsafe. When NASCAR cottoned on to the trick, it imposed specific sealed dampers for these circuits.

As for spring stiffness, the choice of damping is both a matter of art and science. Usually passenger cars have a damping ratio of 0.3 (when ride and comfort are the main targets) to 0.5 (when response is the main target), while racecars are around 0.6-1.0.

Some high-end road sports cars have active, controlled damping using signals from sensors such as steering, lateral

When I am asked what damping ratio to choose, I often suggest trying 0.7 to start. That is because it will give you the quickest ride height recovery

acceleration and yaw rate (gyro) and a damping ratio in the 0.3 region in a straight line for comfort, as much as 1.5 for good turn-in response and back to 0.5 at the corner apex. Defining such active dampers and, even more their controller, requires serious R&D competencies, budget and time. Consequently, they are outlawed in most racing categories.

When I am asked what damping ratio to choose, I often suggest trying 0.7 to start. That is because it will give you the quickest ride height recovery. You will probably not beat the lap record the first time you put your new car on the track with that, but you will not be ridiculous. That is the simplified answer. Oversimplified in fact, because it does not tell you if you need the same damping ratio in bump and in rebound, at low and high speed or even how to define low and high damper speed.

To obtain a better answer you need a two degree of freedom simulation, as presented with the quarter-car model in **Figure 2**.

Mu is the non-suspended mass, Ms is the suspended mass (both in kg). Kt is the tyre stiffness, Ks the suspension stiffness, both in N/m. Ct is tyre damping and Cs suspension damping, both in N/(m/sec).

The road profile, Zt (in metres) is an input, while the vertical moment of the non-suspended Zu and the suspended mass Zs (also in metres) will be outputs.

Most academic quarter-car models are presented this way, but they have their flaws. In my next article I will explain what a good quarter-car model should be, but for now will just explain why such models are unsuited to real suspension design and development. The following remarks are numbered with the same reference on **Figure 2**.

Tyre modelling

We all have seen slow motion video of a race tyre hitting a succession of kerbs. The tyre takes off, lands a few kerbs later and does not stick with the kerb's surface. And yet on most academic quarter-car models, the tyre spring can work in extension!

That's the first major issue. Secondly, only professional team engineers with access to detailed tyre models, or able to undertake complex tyre tests (when allowed), will have access to such essential information and a good knowledge of a tyre's vertical stiffness. It is vertical load, speed, pressure, camber, temperature, slip angle, slip ratio and also excitation frequency sensitive.

I was once told by a tyre manufacturer that a race tyre has no damping. Clearly, everything is relative. It's true that, compared to a suspension damper, the tyre has little damping, but I know that if I let a wheel and tyre fall on the ground from a given height, there will be a logarithmic decrement of the successive amplitudes. So, there clearly is some damping in a tyre, but again only specific tests allow us to acquire such tyre damping characteristics.

It is worth noting that on most seven-post rigs the tyres are not rotating, and therefore have no speed, no slip angle and no slip ratio. As such, the tyre stiffness and damping are not representative of reality. Most seven-post rigs are still useful, but we need to remember that their test results have to be analysed in relative comparison.

And no more than the tyre does the suspension spring work in extension stiffness. We never have seen a spring welded to a spring platform, at least not on a racecar! There is one exception to this though: suspensions with torsion bars where the wheel movement can be controlled in both up and down directions.

A good quarter-car model should (but most will not) consider that the suspension movement could be limited by the minimum spring length in full compression.

Moreover, these simplified models do not consider several other important aspects of suspension stiffness: the spring's possible non-linear stiffness (in fact, there isn't any linear spring stiffness); the possible assembly of two or more springs of different stiffnesses; the spring gap (in full drop it is possible that the spring is not in contact with the spring platform); the spring pre-load; the use of a bump stop (also called a bump rubber) and its gap or pre-load, and finally possible bump rubber hysteresis (that is both stroke and stroke speed sensitive).

Most simplified quarter-car models just use a constant damping, C. The race engineer will quickly find that approach irrelevant because a graph of damper dyno test data will show different damping in compression and rebound, as well as different damping in low and high-speed conditions. That is without even considering damper force vs speed hysteresis.

Then there are the basic mechanical constraints: minimum and maximum eye-to-eye damper length should be considered.

Road inputs, with or without a rotating wheel (in that case, at a given speed), or vertical acceleration vs time as the one induced by an actuator at the tyre contact patch on a seven-post rig will be input options.

The following road profile also needs to be considered: sinusoidal, rectangular and ramp bump and, most importantly, random, or stochastic bumps.

Most simplified models do not consider inputs on the suspended and non-suspended masses such as lateral or longitudinal weight transfer, vertical acceleration from the track banking or slope or aerodynamic downforce.

Challenges ahead

These considerations show just some of the limitations of most quarter-car simulations. There are other challenges too, such as the choice of numerical integrator, especially when we have non-linear and discontinuous inputs. Examples of discontinuous inputs are a bump rubber suddenly becoming active, a damper being fully extended, a tyre off the ground or a fully compressed spring. And all that without considering the possible input of braking or acceleration torque, or slip angle and tyre transient model with relaxation length.

In the next article we will examine the challenges and benefits of a good quarter-car model, and answer the main question that you might use one for: between ride, aerodynamic downforce consistency, tyre mechanical grip and response, what are we looking for, and how do we decide how best to make compromises?

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

Public, onsite, and online OptimumG seminars are held worldwide throughout the year. The Advanced Vehicle Dynamics and the Data Driven Performance Engineering seminars present several theories and best practices that can be used by engineers when making decisions on how to improve vehicle performance. OptimumG engineers can also be found around the world working as consultants for top level teams.

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Time management

The engineering journey of a 24-hour race

By JAHEE CAMPBELL-BRENNAN

Mark Riccioni

Endurance racing over 24 hours is unlike any other form of motorsport. It's a long distance strategic event, involving car, tyre, fuel and personnel coordination

In the middle of the night in the 2000 24 Hours of Le Mans, the leading no.7 Audi R8 suffered a rear left puncture. By the time it had reached the pits and been inspected, one of the mechanics noticed some excessive play in the suspension.

What happened in the following six minutes was like a choreographed display. The team of mechanics removed the rear bodywork and underfloor diffuser, disconnected oil, brake and hydraulic fluid lines, removed the gearbox (complete with rear suspension and brakes), fitted a new gearbox and suspension assembly, put the rest back together and set the car back down the pit lane.

It was very clear to see this was a repair that had been anticipated in the car's development, and rehearsed intensely by the team. It was obviously designed around the fact it is quicker to replace a whole sub-assembly than an individual suspension component.

This is but a quick glimpse into the preparation and rehearsal that goes into a 24-hour race entry, and highlights the level of professionalism and desire to win that teams bring to the competition.

Endurance racing brings a whole new dimension to competition. If you suffer a puncture or mechanical failure in sprint championships such as DTM or F1, at best you lose the race, at worst it's a retirement. In a 24-hour race, you might still stand a chance.

The 24-hour racing arena is much more of a strategic event than traditional racing. It's not just about having the quickest car over a lap, key to success is tyre, fuel and human management.

So, how exactly do the trackside teams approach car development and set-up to challenge for a win? How do mechanics prepare for unforeseen repairs due to mechanical failure or crash, and how do the engineers approach the development of the car over the race event?

In this article we'll follow the engineering journey of teams from the first pre-race tests at the beginning of an endurance championship through to the final race debrief, exploring exactly how competition at 24-hour racing is prepared and executed.

Lead up

The preparation for an endurance event such as Le Mans starts in the preceding race season of the FIA World Endurance Championship, or European Le Mans Series (ELMS). The pandemic this year has turned things upside down, but it usually means a team new to WEC have had a minimum of two to three 'mini' endurance races prior to the big event.

For other races, such as the ADAC TOTAL 24-hour race on the Nürburgring Nordschleife, the NLS series (formerly VLN) gives a handful of races at the same venue before the main event, allowing time to practice.

The Rolex 24 at Daytona is a slightly different challenge as it hits the peak first, kicking off IMSA's season in January. In this case, pre-season testing is clearly of utmost importance.

'Last year we did two 12-hour test days at Daytona before the 'Roar before the 24' [pre-race testing at Daytona],' recalls Todd Malloy, race engineer with BMW Team RLL. 'The components on the car ran those tests, then they ran all of the Roar, which is like four days of running.

'So you have nearly 48 hours on all the components to understand their durability. These components all then get swapped out for new before the race.

'It's important to do this so everyone can be working together as a team and get some mileage on the cars.'

On arrival at the race weekend, first order of events are the free practice sessions. These are an opportunity to put some miles on the car, gather data and let drivers familiarise themselves with the track. It's also a chance to dial in and work on the suspension and aero set-up for the race ahead.

But for some of the larger teams in the top classes, these practice sessions take on a slightly different meaning.

'Free practice for us is usually a case of validating simulations to ensure correlation to our analytical work,' comments John Steeghs, team manager for Toyota Gazoo Racing LMP1 operations.

BMW Motorsport

BMW Team RLL has a good understanding of what it takes to win in endurance racing, taking first place at the 2020 Rolex 24

Mark Riccioni

Weather can change dramatically over a 24-hour period, and understanding wet set-up changes to driveability is critical

'We go through several set-ups to double check if the data is what we expected to see from our simulations.'

Using vehicle dynamics simulations with mathematical models of a particular vehicle at a track like Circuit de la Sarthe allows hundreds, or even thousands, of set-up options to be evaluated digitally before ever running the car on a track.

The objective of practice sessions then shifts from running through set-up options to find the best configuration, to running a select few scenarios to put trust in the models.

'On the Mazda DPi project for Daytona, we use simulation to find a starting set-up based on the previous year's race, or test events at that circuit, and we then look at how to adapt the set-up based on driver feedback through practice,' says Leena Gade, race engineer and head of vehicle dynamics at Multimatic.

A unique factor of endurance racing that sets it apart from sprint racing is the same car is often shared by drivers with a spectrum of abilities

'If the driver is reporting a lot of high-speed balance issues then that obviously highlights an area we need to work on. In this case it could be aero, but also how the car generates its tyre temperature, which is a mechanical issue that needs to be addressed.'

As ever in engineering, there are multiple approaches to the same problem. There is one thing that most will agree on though: 'The objective at the beginning is just to maximise track time,' confirms Steeghs, 'as this is more valuable than everything else. If we miss track time, we are unable to validate set-ups, systems and tyres on the car, which will bite us all weekend.'

For the less resourced privateer teams, this can be the first occasion the track, racecar and drivers all come together. Pre-race practice sessions are therefore vital for tuning the car and for drivers to become acquainted with the conditions.

'We really approach these sessions with the aim of finding a consistent, comfortable set-up that performs well in all scenarios. Driveability and driver comfort over the race can become priority, rather than outright pace,' explains Jamie Gomeche, race engineer at Phoenix Racing, with experience at Le Mans.

'A big thing to focus on is ride. We'll be looking for things like the car bottoming out at the end of straight sections, or bouncing around too much. The set-up preferences for the drivers generally converge around these things.'

A unique factor of endurance racing that sets it apart from sprint racing is the same car is often shared by drivers with a spectrum of abilities. The objective is therefore to find a set-up that is in a certain 'window', which all three drivers of the car feel comfortable with.

With a mix of amateur and professional drivers at the wheel in privateer racing, the race set-up is often chosen to ensure the amateur driver is most comfortable and can get the most from the car. The more experienced professional driver then works around this. It doesn't help anybody if you arrive at a race set-up that makes the pro 0.2s faster round a lap if it makes the amateur 0.5s slower.

'You need to find a compromise that allows them to keep the car close to the limit,' adds Gade. 'You'll never have a car that has its best performance throughout the whole race, so there's less reliance on finding that. It's about making sure your drivers are comfortable throughout.'

Qualifying

Once practice is out of the way and a solid race set-up is found, teams' focus moves to qualifying.

Qualifying and race set-ups have a quite different set of motivators. The aim of qualifying is to draw out the most performance from the car for a short period of time. Qualifying runs are performed with low fuel loads and brand new tyres, great conditions for one or two flying laps, but not indicative of the whole race.

'We generally don't have much difference between qualifying and race set-ups but, for example, on a long run, the balance can start to lean into oversteer. If we do change the set-up, it might be to start the run with a little understeer so, as the tyres degrade, the car will come into a balance window. Qualifying will be a more neutral set-up throughout as degradation isn't a problem,' notes Malloy.

'With a 24-hour race, though, where qualifying doesn't matter so much, we don't spend a whole lot of time preparing for qualifying, we'd rather spend the time preparing for the race.'

Chassis balance can be adjusted by manipulating roll stiffness, the distribution of which between each axle influences this by changing the relative wheel loads. Most commonly, adjustments to roll stiffness are made by adjusting the ARB (anti-roll bar) leverage and adjusting dampers to modify the damper curves. High roll stiffness can be utilised to increase the rate of energy input into the tyres, quickly bringing them up to temperature for qualifying, but on longer runs this can be a disadvantage.

'Normally if you've got a quick car for a race, it will do quite well over the qualifying event, but the inverse isn't always true.

'If you have a quick car for qualifying it can be quite awful over a race as the suspension is so aggressive, potentially working the tyres too hard, or simply being difficult to drive consistently,' Gomeche adds. 'Depending on the driver, some will want a bit more rotation at the rear as they perform better with a slight oversteer balance, while others prefer the safety of an understeer balance. In the race, the aim is to have something with more margin for error, requiring less concentration.'

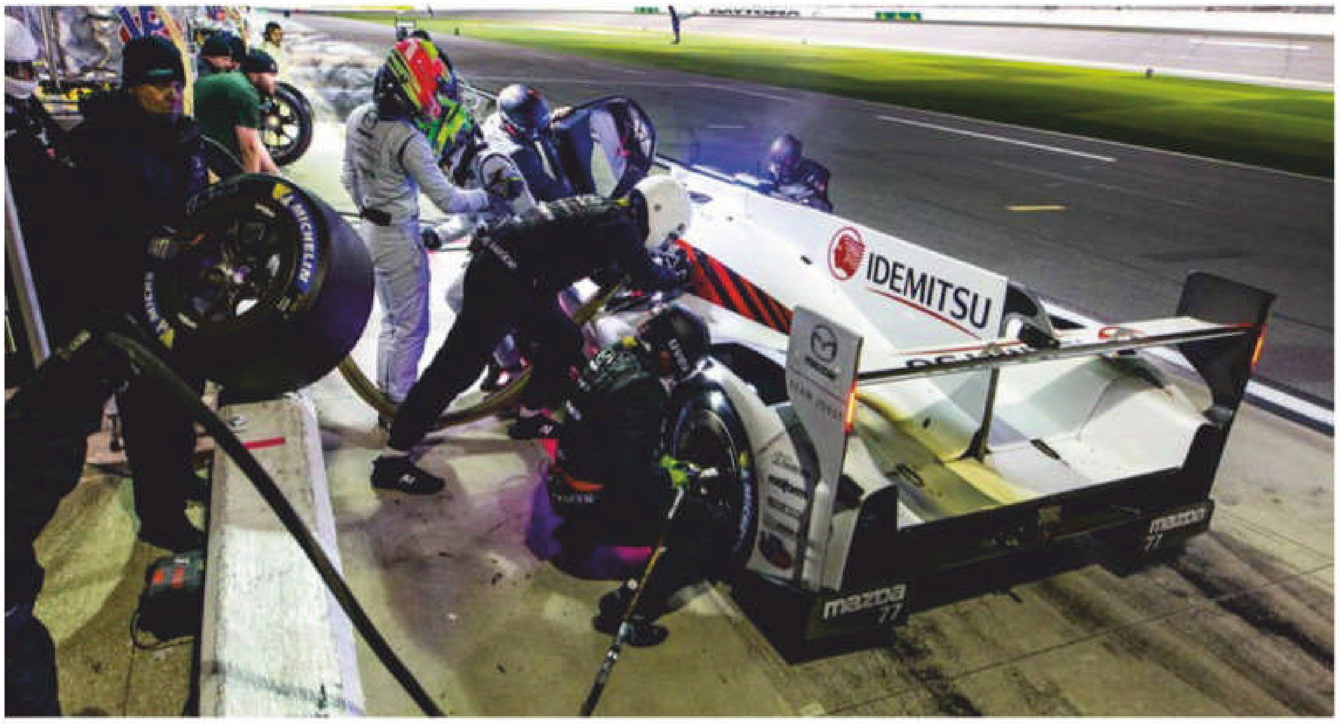
In an endurance event, it's all about managing this tyre energy to ensure they stay in the right temperature range. Too cold and the compound isn't elastic enough, too hot and you move the tyre into the blistering, or graining, danger zone as its ability to resist shear stresses diminishes.

Naturally, wet racing adds yet another dimension to set-up considerations. With a film of water affecting chemical adhesion between the contact patch and track, tyres become more sensitive to load variations. Wet tyres are also of a softer compound and feature tread blocks, which contribute to generating more internal friction and heat. Because of this, they can be prone to overheating.

'In the Nürburgring 24 this year [held in September], it was a wet / damp qualifying event so we made changes to reduce the roll stiffness, creating a best suited set-up for those specific conditions over one lap,' Gomeche recalls.

Mark Riccioni

Wet track surfaces influence chemical adhesion at the contact patch and require a different approach to car set-up



Multimatic

Preparation is key to handling the unexpected, and teams will run through numerous potential scenarios prior to the race

Race preparation

Once qualifying is over, the race preparation starts and attention shifts towards team management and preparing the car and equipment for the rigours of the 24 hours ahead.

Most engineers will tell you that the largest difference between sprint and endurance racing is that it's less about outright performance and more about planning, preparation and execution.

'The biggest thing you need to do in a 24-hour race is minimise mistakes,' says Chris Mower, team manager at BMW Team RLL. 'They do happen, so you just have to make sure you have the procedures in place to handle them. Then, if you do have any issues, hopefully you've preempted them and have procedures for getting the car back on track as soon as possible.'

It's a sentiment echoed by Malloy: 'We have a very thorough pre-event strategy meeting, discussing the overall plan and what to do in case of any eventualities. If you go off, the grille gets covered in grass and temperature skyrockets, you better plan for that. Similarly, with track hazards. At Daytona, the Bus Stop chicane has some savage kerbs so we need drivers to avoid those or we won't have a car to finish with.'

Having procedures and processes in place removes some of the guesswork and potential pressure of being hit with unexpected occurrences. Putting together a reaction plan allows issues to be dealt with in a controlled and considered manner, removing an element of risk from panic.

In such a long race with so many variables, reducing the potential for mechanical failures is good preparation. Hence why it's common for teams to strip their cars down to the chassis and swap as many high-risk parts as a wallet permits before the race.

'I once worked with an LMP2 team who had, in previous years, effectively replaced the entire car after the last qualifying event at Le Mans,' highlights Gomeche. 'They stripped the car down to the tub and rebuilt it with new parts. Not because anything was wrong, it was more of a win-at-all-costs approach so they were trying to remove all risk possible.'

Make no mistake, 24-hour races are huge events, with great kudos afforded the winners, both in the currency of respect within the teams and commercial opportunities. Losing the race from a leading position due to mechanical failure is a difficult thing to accept. So, if you can afford to, you plan around that.

In the race, the aim is to have something with more margin for error, requiring less concentration

Jamie Gomeche, race engineer at Phoenix Racing

Steeghs confirms: 'We usually bring around six front ends, six rear ends and six underfloors to the event to cover failures, all prepared in race set-up before the race. We shake down all the parts at our Spa test a week before the official Le Mans test day to ensure they are all tested and ready to go. This way, everything we use has been set-up on the car so we have nothing to worry about.'

Team personnel

Managing the team to ensure each role has enough support requires a lot of personnel in addition to the usual crew complement at IMSA or WEC races. Creating a framework in which each individual can complete their role in the most efficient way is especially diligent.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'In a 24-hour race such as Le Mans, where each team member has much more of an impact and role in the overall outcome of the race, it's important to leave people in their value and provide the best environment for them to conduct their responsibilities.' notes Steeghs. 'We usually take two additional people for tyre management to help with running them back and forth. We also bring extra personnel to manage engineering tasks like data analysis a little closer than we might in shorter races.'

Contrary to popular belief, budgets are not infinite, even at the very top of the sport. Teams will also make repairs to damaged components during the race where possible, as Steeghs explains: 'As the main composites team is usually involved with pit stops, we take additional tech support to work on things such as repairs out in the back. We have had a case in the past where we repaired a nose piece and then put it back on the car later in the race.'

Of course, repairs add weight, so good judgement is needed to decide whether a part is to be repaired or replaced. Prototypes, in particular, are sensitive to balance changes caused by altering weight distribution. In a close battle, a bad call here can cost a victory.

As races can be won or lost based on accurate weather prediction, TGR also brings several team members whose sole responsibility is rain spotting! Located in key spots throughout the race their job is to give first-hand updates on weather conditions.

As the race settles into a rhythm, the cars are mostly maintenance free over the next 3000 miles (4800km) or so. Occasionally, a small amount of oil must be added to top up the sump as the engine burns oil, and brakes are a common wear part, so discs and pads are also changed at some point.

'Part life for things like brake discs is generally gauged manually through testing,' explains Gomeche. 'After fitting new brakes, you may perform 150km of testing and then measure everything. With the level of wear you see, you can then extrapolate a wear per km figure and apply that to estimate when you'll need to do work like that.'

Unlike shorter races, race strategy for 24-hour races is fairly open. There are some baselines established, such as driver order, which require some consideration. Generally, the most experienced drivers take the most important tasks to start and finish races.

'You know fuel capacity, useable fuel and also fuel consumption, which automatically dictates how long your stint is going to last. I typically use this to construct a strategy for the full race to understand how long I will spend in the pit lane, including time driving in and out of the pits,' explains Gade.

Twenty four hour races are broken into phases, the endurance part from the beginning, the sprint for the final stages. The different phases have distinct requirements from both car and driver.

'In terms of prepping the car, it's important to make sure the car and drivers are strong in the last phases of the race. The racing hots up in the final four to six hours or so, so you plan to have your car in good condition during these stages, with fresh brakes etc.' notes Malloy.

This can also play into your driver sequence. You'd want your more experienced drivers in the car to handle the initial rush after the start and also the potential battles in the final sprint phase of the race.

It can also be wise to ensure there are no driver changes during the transitioning hours of dusk and dawn to minimise the risk of mistakes.

Toyota Gazoo Racing

Ensuring the whole team is effectively engaged, and all working to their strengths and value is key to managing a 24-hour race

TGR also brings several team members whose sole responsibility is rain spotting!

Once the lights are green and drivers settle into the race, it's largely just a case of managing pit stops and track conditions for the engineering team.

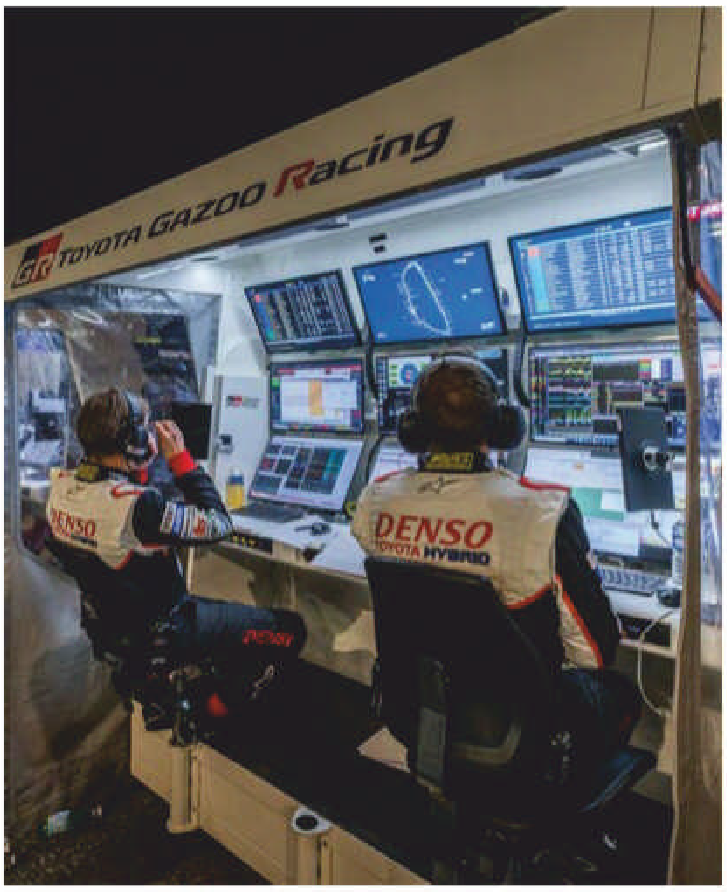
The race

To do this, engineers use run sheets to keep track of things such as race conditions, pit stops, fuelling and lap times from the pit wall, and these are a crucial tool for the race engineer to keep a handle on things. They allow you to plan and control a race.

'Run sheets help you keep an eye on what's happening in the moment, but also what's going to be happening in the future. If you follow the plan, you'll know in three

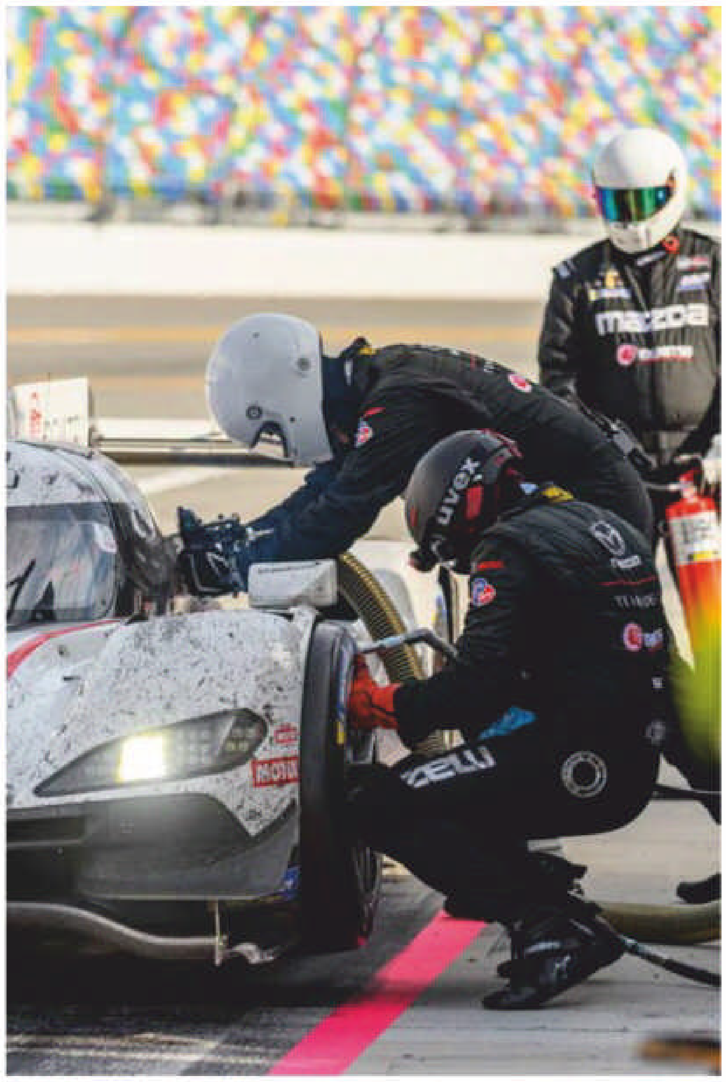
Mark Riccioni

The latter part of a 24-hour race is closer to a sprint than an endurance event, requiring a change in strategy



Toyota Gazoo Racing

The amount of data transmitted to the engineering station is vast



Multimatic

Debris accumulates on the aerodynamic surfaces over the course of a race and impacts performance. Planning for this is important

Multimatic

Drivers need briefing on conditions before their stint. Professional drivers will usually start and finish an event

Mark Riccioni

In 2020 at the Nürburgring, rain forced an overnight stop and track conditions were vastly different on restart

stints time whether you'll still have enough driving time, or whether at the end of the race you're going to have to do a quick stop or splash of fuel,' concurs Gomeche.

The race engineer also has responsibility for engaging the mechanics, which means communicating when pit stops are coming up and what needs to be done to the cars.

'If we're doing a 45-minute stint, 15 minutes before the car is coming in we give a heads up that we're entering a pit window,' adds Gomeche. 'The driver can come in at any point during that window, so it's a cue to get helmets on and be ready.

'A normal pit stop can consist of new tyres, clean windscreen, refilling the drinks bottle, a download of the ECU data and, depending on the sequence, a change of driver.'

Before a driver change, the incoming driver must be briefed about the conditions around the race track as they need to have some situational awareness and get up to speed quickly. They can also take information about race conditions through observing how the outgoing driver is driving.

'Drivers will use the inboard cameras to take visual cues from how the current driver is handling the car through a lap, taking cues on braking and corner entry etc. This can help them understand how the line has changed from their previous stints,' explains Gade, continuing, 'aero performance across the race also degrades as the cars get covered in dirt. Unless you spend time during pits to clean the important areas of the car, you can noticeably lose downforce over the 24 hours.

'There will always be damage too, whether it's running over the kerbs and damaging your splitter or damage from contact or debris. These things can definitely affect aero performance, which may dictate a repair.'

When we talk of tracks evolving, what is being referred to is the rubber laid down as tyres wear. Consequently, grip levels increase as the surface matures. With a big grid like that of the 2020 Nürburgring 24h where 97 cars competed, that's a lot of rubber, and eventually a point of equilibrium is reached where the rubber film becomes so thick it starts marbling as the top layers shear off.

Rain on a mature surface adds further interest and the difference in grip between is exaggerated in latter parts of the race.

Not only is the transition from slick to intermediate / wet tyre somewhat of a gamble, but the effect of the rain in 'washing' the track can be especially pronounced, as Gomeche experienced first hand this year.

'We had a pretty strong stint in the Audi in at the beginning of the race at the Nürburgring, but after seven hours the race was suspended for almost 10 hours overnight due to the heavy rain.

'The car was initially performing pretty well, with the factory car in P1 and the sister car not far behind at the point of the red flag. But then at 8am in the morning when the race re-started, the car's balance was way off. We were running a bit of a wet set-up so we had taken out some roll stiffness, nothing big, but the car was behaving like it was on ice. We changed back to a dry set-up during a stop and the car came back to us again.'

Sometimes, even with all the data and experience, things still aren't straightforward.

Battle of will

It's wise to keep an eye on how your competition is executing their race in this sense. 'Most teams run two cars, and what they'll do is split their strategies at certain points. They'll keep one on the standard strategy but then deviate from that with the other car to make sure they have everything covered with respect to safety car events and things like that,' notes Mower. 'You need to look at when teams start peeling off on that alternate strategy, and then decide whether you have another car that follows so you've got them covered, too.

It can turn into more of a chess match as far as strategy goes in that respect.'

As the race settles into darkness, it becomes a battle of will as drivers work to maintain concentration and stay consistent through their stints. At this point, the engineering team are in constant communication with the drivers through the race engineer.

It's a little more involved than setting them out down the pit-lane and telling them to just do their best. Drivers want to know what's going on around them with their competition, what kind of lap times they should be aiming for and additional information such as any fuel saving they should be employing during the stint. Settings on the car such as TC and engine map changes can also be communicated.

As the race progresses, the race engineer sometimes needs to encourage more 'economical' driving styles, managing both the drivers' energy levels and the cars' enthusiasm. This is where data analysis comes in helpful in relation to specific problems.

'In a race I was recently involved in, we had a problem with the tyres as they were falling off massively,' recalls Gomeche. 'We couldn't double stint them unless they were treated very carefully in the first stint.

'We have various maths channels we can create to process the data to show slip levels, as well as over or understeer values.'

Data processing

Maths channels are used to algebraically manipulate measured signals from the cars' sensors. They allow engineers to process data to deduce patterns and view certain performance characteristics that aren't possible using direct measurement as they aren't physical parameters.

'In this case, the data was showing a particularly high level of slip in the driver's previous laps so we told him to go a little easier. It also showed he was getting a bit of snap oversteer in turn two so he needed to take it easy through there.'

Occasionally, the race engineer's role transcends data and maths channels and steps into the realm of emotional support. A familiar and encouraging voice can make all the difference as fatigue sets in.

It's not just a challenge of mechanical endurance, it's also a human challenge

This is the element of endurance racing that makes it so special. It's not just a challenge of mechanical endurance, it's also a human challenge, and being open and trusting each other as a team is paramount to success in 24-hour races.

Post-race

If all goes well and a team clinches the win, the post-race debrief wraps up the race and lines up the celebrations.

'The whole team is exhausted, so we make it quick, but we take notes on what went wrong and immediately take steps to ensure the mistakes aren't going to happen again. We don't just focus on the bad, though, we also make note of what worked and what we'll want to repeat,' concludes Mower.

With so much effort and energy going into winning these races, the way this part of the process is approached can have a huge emotional impact on drivers, engineers and the wider team.

This is something Toyota Gazoo Racing may know better than others, as Steeghs recounts: 'In 2016, after leading for so long, we had a mechanical failure with the no.5 car on the last lap of the race. The car crossed the line in second position and did the same number of laps as the winner, but not to be classified was really very difficult. It's something I still struggle with today.'

Endurance racing is an event people tend to love or hate. At hour 18, as the sun begins to rise, the only thing keeping you performing is mental resilience. You have to really have that passion for it. As with most things in life, the reward must outweigh the sacrifice for it to be meaningful.

'Having worked in both sprint and 24-hour races, the main difference as an engineer for me is that you have such a huge role in the race. In simple terms, with sprint you generally just work towards a good set-up, fill the car up and set it off for the next 30 minutes or so. The race itself is largely out of your hands,' says Gomeche. 'With 24-hour races, you have such a large input into the progress of the race. Even with the mechanics doing a consistent job with the stops, the whole thing is a team effort and everyone involved plays such a huge role in executing the race. It feels like you're the most connected to the race as you can be, which is the appeal for me.'

Effective preparation, good team management, a passion to win and the mental resilience to stay focussed until the end

Besides, in face of disappointment, there's always a silver lining, as Steeghs recalls: 'Even after our failure in 2016, it will always stay with me how emotional the other teams, even the ACO, were over the event, too. They supported us and that was one of the most fantastic feelings I've ever had. It's such a community event, and that is certainly unique to endurance racing.'

With the new regulations in 2021 the cars might be changing, but the formula for success is enduring. Effective preparation, good team management, a passion to win and the mental resilience to stay focussed until the end.

Endurance racing is clearly considerably more than the sum of its parts.

Toyota Gazoo Racing

During a 24-hour race every aspect of the strategy and car preparation is maximised for performance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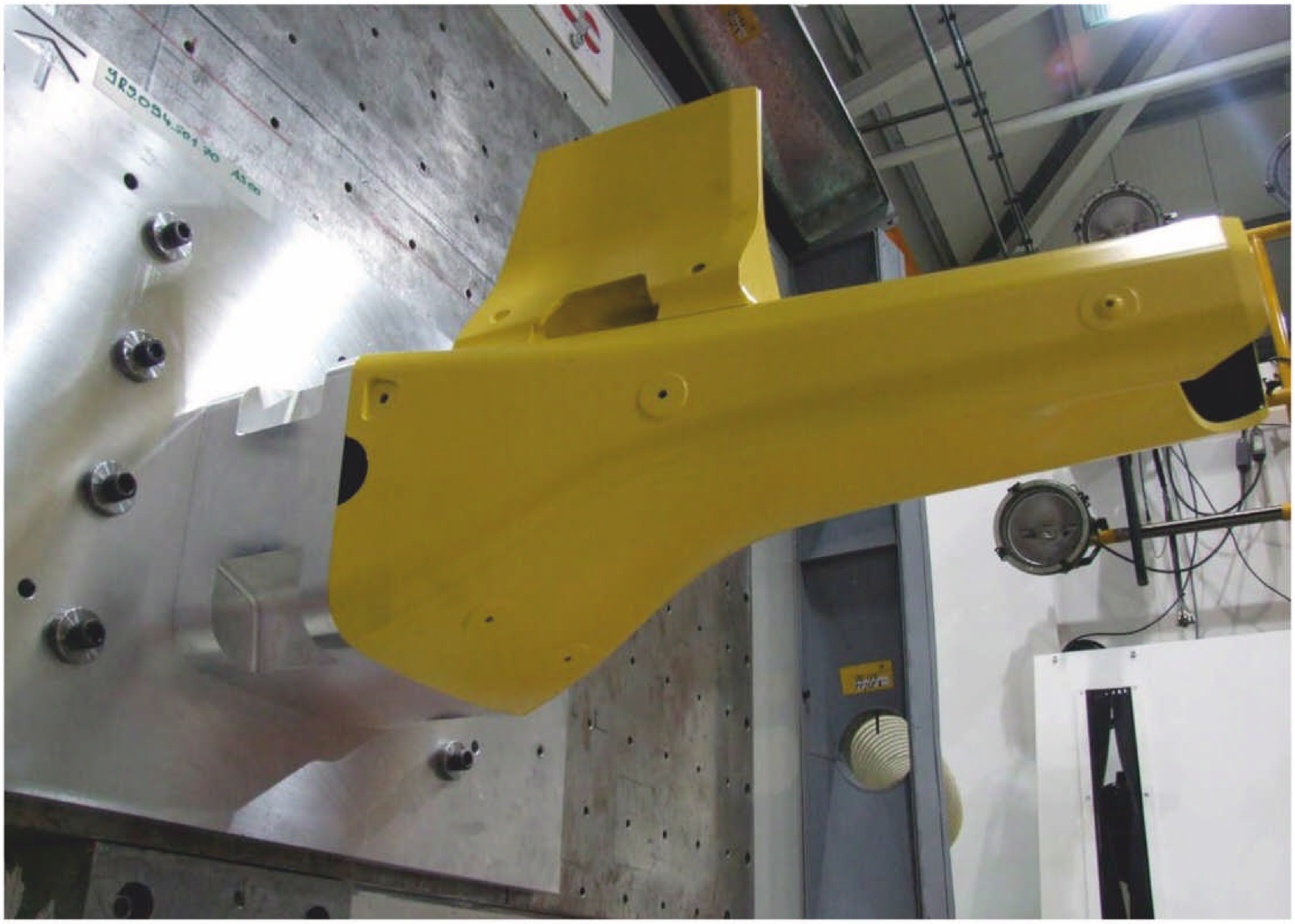
First impressions

Cranfield Impact Centre plays a crucial role in ensuring the safety of racecars. With tougher regulations coming into force next year, *Racecar Engineering* investigates

By ANDREW COTTON

Racecar and driver safety has come a long way since the 1983 FIA regulations required the introduction of an additional box structure into the nosecones of Formula 1 cars

FIA-approved crash testing facilities have been created in order to conduct repeatable, measurable tests



Crash test speed was 10m/s in 1985, but in 2021 will increase again from the current 15m/s to 17m/s. That equates to an almost 50 per cent increase in energy absorption

Hearing the news that a car has passed its crash test is now commonplace in racing circles. As advances in computer software through the design phase improves, so does the ability to predict how one will deform, but it was not always the case. Racecars from all series have often failed their first impact tests before heading to the track, particularly as rules tightened at key moments and design teams had to react quickly, perhaps with the risk of losing performance.

Long gone are the days when crash testing meant dropping a car, or component, from a crane into the ground to estimate the likelihood of a driver surviving the impact. Also behind us are the days when racecars would not even be tested, extra material only being added in order to improve performance, rather than driver safety.

Today's crash test criteria are stringent and the results are clear to see. Advances in composite materials, accident investigation and computer design have all helped create regulations that have yielded some of the safest racecars ever produced.

Yet, in order to approve car design *before* the cars hit the track, a component, or car, needs to be properly evaluated. And for that to happen, FIA-approved crash testing facilities have been created in order to conduct repeatable, measurable tests. One of these is housed on the campus at Cranfield University in the UK, and it is not unusual to have Formula 1 and WEC cars pass through the doors to reach certification for racing.

When we visited the facility, essentially a hangar in which all the test and measuring equipment is housed, there were a range of vehicles that either have been tested, or are about to be, including a Dakar tube-frame chassis and, sitting next to that, a wheelchair. In a box next to the wheelchair are bolts which hold the Halo device in place.

This is not just a racecar test facility, and those running the tests are not necessarily racing fans. Their sole goal is to establish if a vehicle, or component, is fit for purpose, and they have been doing that for 40 years.

Primary function

In order to understand the challenge that the crash testing process poses, a design team must create a monocoque, or tub, from which the component parts of the racecar are hung. These include the front crash structure, side impact protection as well as functional items such as the front suspension and side radiators. However, the tub's primary function is to be the survival cell for the driver in the event of an accident, one in which the body will be as protected as possible.

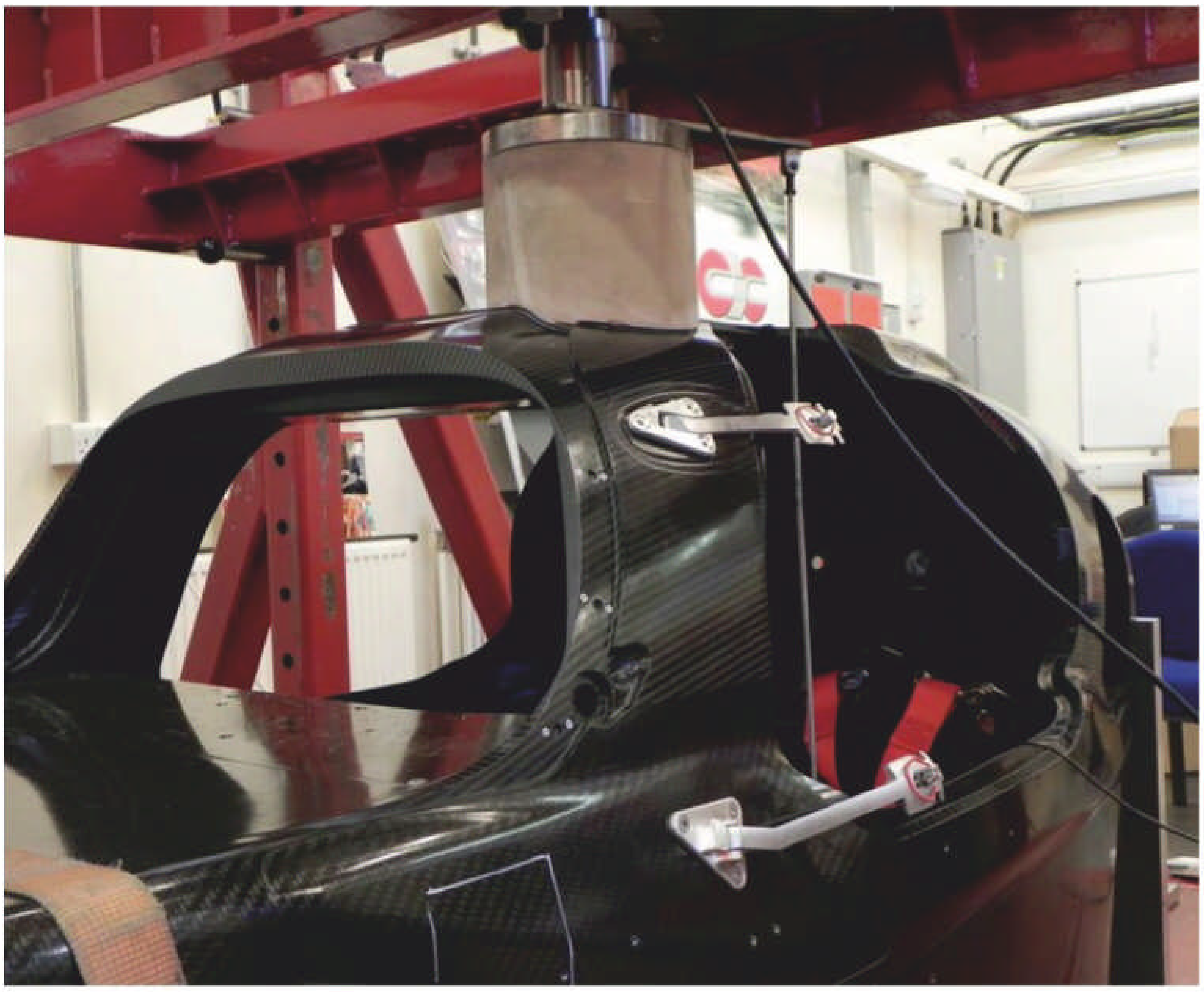
From the roll hoop above the driver's head to the bottom of the tub, normally sculpted for aerodynamic efficiency, the structures have to withstand enormous pressure in a combination of both dynamic and static tests to prove not only strength, but also the correct deformability for a given part.


Williams' FW10 was the company's first carbon tub car but the composites team was unsure whether or not it would pass the crash testing criteria so came up with a back up plan of a honeycomb structure in the nose

The former essentially establishes deformity in the event of an accident, the latter ensures the parts are fitted well enough that they don't simply fall off at a measured minimum impact speed.

The combination has produced cars that are capable of withstanding impacts that previously may have led to injury or death of a driver, but there is more to the tests than simply crashing a component, car or wheelchair into a solid wall. In order to prove the parts are able to withstand impact, each test must be measurable, repeatable and accurate. Data gathered must then be shared with the design team and governing body to confirm the car is safe before it is put into production, or allowed to race.

In order to do that, not only must the equipment be maintained to the highest level but the latest technologies need to be incorporated, including high-definition cameras, accelerometers and computer software. The results must be fully understood too, in order to provide meaningful reports back to the involved parties.


There is a misconception that static tests are easier to pass than dynamic, but withstanding pressure is a challenge

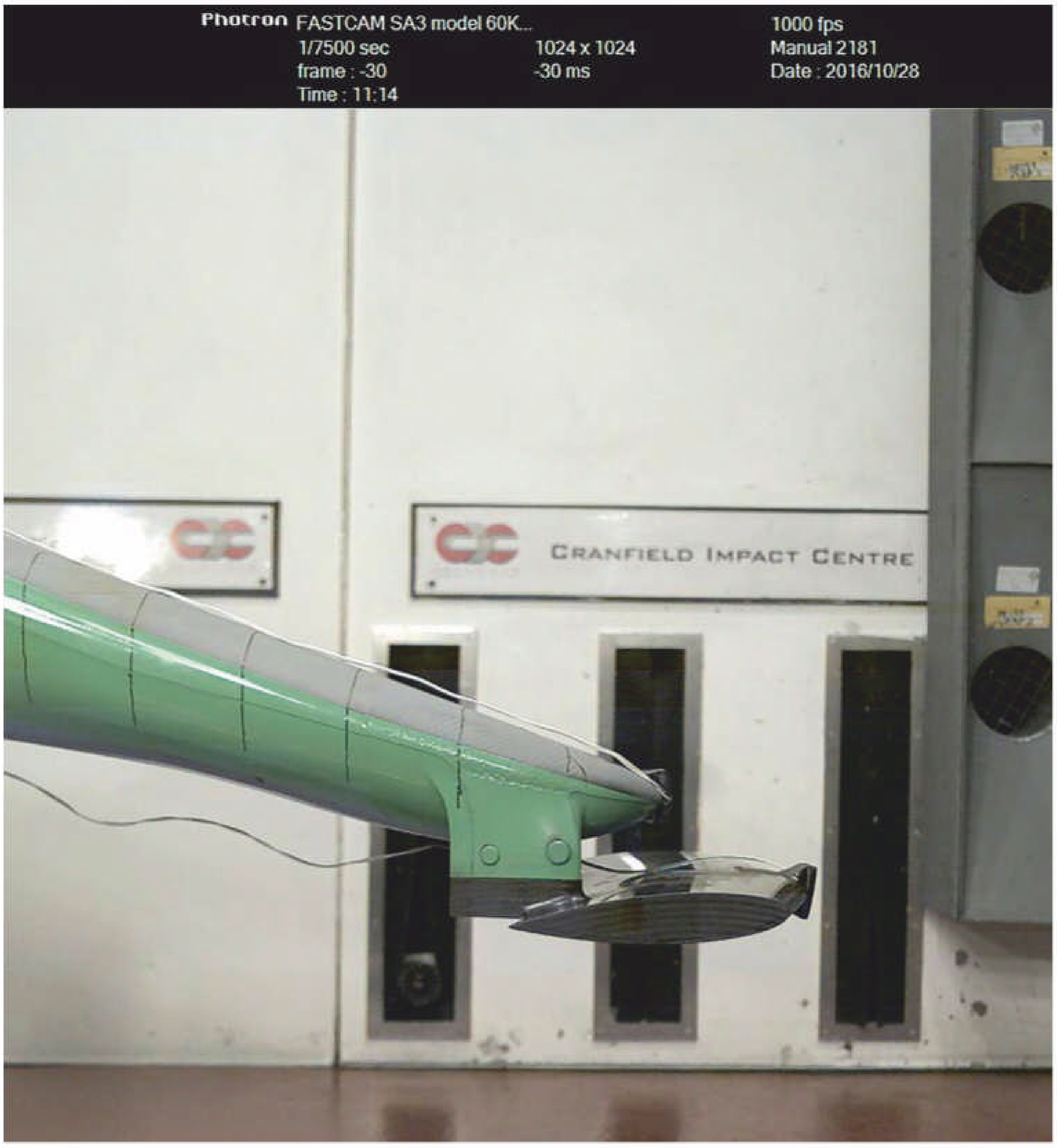
History repeating

The history of crash testing at Cranfield stretches back to the mid-1980s. Prior to that, teams would generally only strengthen their cars to increase torsional rigidity for the purpose of improved performance. Lotus and McLaren brought carbon chassis to Formula 1 in the early 1980s and, although the structures were stronger, and protected the driver better, it was not necessarily for that purpose carbon tubs were introduced. Lighter and stiffer, the cars were going to be faster than their aluminium-bodied competitors and, as such, had a performance advantage. However, back then there was less knowledge of how to lay up the carbon fibres for strength and specialists were needed to ensure the finished racecar was as strong, or stronger, than an aluminium one.

Even then, actually testing the car for strength was not a priority. 'There was a regulation change in 1983 where we had to

There is more to the tests than simply crashing a component, car or wheelchair into a solid wall

The latest high-definition cameras record tests and results can be sent digitally in real time if required



Much of the current development work in F1 centres around reducing the likelihood of parts falling off cars in crash scenarios

add a bit of extra box section on the front, which I remember was a bit optimistic,' recalls Brian O'Rourke, former chief composites engineer at Williams Grand Prix Engineering. 'Those things were not very substantial.'

The calculation at the time was that an average human being could survive an impact of around 20*g*, or 20 times their own bodyweight. Due to the fitness levels of professional racing drivers, the limit was raised to 25*g* for the purpose of testing.

'It was very rudimentary, but they came up with an energy level that equated to a speed of 10m/s, and that was intended for the start of the 1985 season,' says O'Rourke.

Pendulum swing

At that time, IndyCar had already started testing its chassis for high-impact accidents, particularly against the walls that line an oval track, and Formula 1, which typically sees lower-speed accidents, was right behind.

The process used in the first crash tests involved a pendulum rig. A block was strapped to it and swung into a the test object at the required speed. Originally, Cranfield's rig was designed to test railway carriages so for the purpose of testing Formula 1 cars it was well within its tolerances.

For O'Rourke, who was preparing the Williams FW10 for the 1985 season, this was just the latest in a series of obstacles that had to be overcome for the design team. The FW10 was Williams' first carbon monocoque and the opening round was in Brazil early in April. Because of the time it took to ship a car, the crash test had to be completed early and the team was not at all sure it would pass the required test. So a back-up plan was devised, a honeycomb structure in the nose that could be attached to the FW09.

'I had already done the thumb calculations on it and said to myself that there was no way this was ever going to do the job,' remembers O'Rourke. 'I don't think these guys had any idea of how far adrift the cars of that time were, so the only way to achieve this was to put a big honeycomb structure on the inside of a standard nosebox.' The first test was done at half speed and, while it stood up to the impact with only 50 per cent deformation, at full speed the nose collapsed so fast that the rig broke. 'I had taken bin liners to bring the parts back, but there was nothing left to recover,' says O'Rourke.

After a long lunch, taken while the rig was repaired, they tried again with the honeycomb structure and this time it passed. 'It was a reasonable absorption curve, so that was the starting point. Actually, I had made it a bit too stiff, so what happened then was that it pushed the front of the bulkhead into the monocoque, which wasn't intended.

'We had a bit of a re-think about beefing up the monocoque and went back a week later. We managed to pass that one.'

This may have been the early days of crash testing, but the same issues have arisen ever since. Above the door to the Cranfield test rig today is a Formula 3 chassis that had been subjected to the side impact tests mandated by the FIA recently. The holes in the side of the monocoque indicate it suffered the same issue as Williams nearly 40 years earlier.

Structures have to withstand enormous pressure in a combination of both dynamic and static tests

With such pressure on teams to produce cars capable of passing the crash test before being certified to race, there is a clear loophole that, according to folklore, was often exploited: building one car specifically to pass the test, but not the same specification as the car on track. This was a clear area of danger that had to be addressed.

When Formula 1 went to high noses with the front wing hung from the underside on pylons, these were not necessarily the same as those used in crash testing. 'There is a lovely story about an F1 team who aren't around any more, but who went to the first track test in Spain and the first time the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It is not just racecars tested at Cranfield Impact Centre, all forms of technology come under similar scrutiny

car left the pits the front wing fell off,' says O'Rourke. 'It was the one intended for the crash test, not for track running.'

Martin Donnelly's accident at Jerez in 1990 led the FIA to change crash testing protocols, too. While the monocoque had passed the test, there was a clear failure in the chassis, which split in two during impact.

'From 1991 onwards, you did all of your tests on a data chassis, and every other chassis had to go through five squeeze tests as today, so you have to show that every monocoque you build will not deflect more than the original one,' explains O'Rourke.

Another test that was introduced following the 1991 season was on the roll hoop, which required the highest structural part of the racecar to withstand a pressure of seven tonnes. It was one of the biggest changes in safety regulations and, while designers focussed on lowering the c of g by using composite materials, when the regulations became even more stringent in 2001 they were forced to go back to metallic inserts within the composite structure in order to meet the strength required.

More recently, additive manufacturing has allowed for a titanium roll hoop to be fitted and that is what is used in today's F1 cars.

'Today's ones look very much like they used to in the 1970s,' says O'Rourke. 'If you get down to it, metallic structures are back in, but there has been a lot of heartache and lost sleep since then over passing these tests.'

The big squeeze

From testing the front of the car, the FIA then moved to testing the monocoque with a combination of squeeze tests and dynamic tests. Both are still used on racecars today, though now they have to withstand greater levels of pressure and impact than ever before, and passing the test is about to become even more difficult.

The FIA is soon to release a new set of criteria for the test houses to adopt, and Cranfield Impact Centre has been directly involved in its development.

'This goes further on all technical aspects,' confirms James Watson, Cranfield Impact Centre manager. 'What specific regulation crash test is needed? Is the instrumentation fully calibrated? Is it traceable? Can you record it repeatedly when you measure the acceleration? What range of uncertainty is your measurement?

'There is a regulated method that the whole test should be documented and approved. When you take any crash test it is impossible to perform exactly the same crash test twice. You could say the friction might change, or the humidity or temperature, and controlling those is what makes sure the test is repeatable. That's what the purpose of the thorough preparation is.'

Under the new regulations, Formula 1 crash testing will move to a faster crash test speed, up from 15m/s to 17m/s, with a slightly increased mass. 'The speed increase doesn't sound like very much, but the energy will go up from 88kJ to 130kJ, because it is $1/2mv^2$. Any increase in velocity is a massive increase in energy,' notes Watson. 'Therefore the energy absorbing capabilities of the vehicles will be significantly improved.'

Having accurate measurements is one thing, but the data analysis afterwards is also critical. 'The nose cone, for example, has to pass different criteria to absorb the energy within the first 60kJ,' explains Watson. 'We then perform the analysis demanded by the FIA, which is unique. For example, you have to make sure the nose cone doesn't come off after a glancing blow before the car goes into a solid wall. So they put a large force into the side, 40kN, and hold that for 30 seconds. That's a serious test, but it stops the nose cones falling off in the initial stages of a crash.'

High in fibre

Bcomp and YCOM have collaborated to develop and manufacture the world's first natural fibre crash box for motorsport, the Front Impact Absorbing Structure (FIAS), using Bcomp's powerRibs and ampliTex material.

Designed by leading advanced technologies expert, YCOM, and using higher performance ampliTex flax fibres, it proves natural fibres can play an important role in structural and safety-critical parts.

The crash box is designed to optimise the performance of the ampliTex natural fibre reinforcements and was tested at the FIA-approved test house of Politecnico of Milan. The impact test results achieved were in line with a traditional carbon fibre structure. The material not only shows the desired crash behaviour required from a safety perspective, it eradicates the danger of sharp splintering. Furthermore, natural fibre composites waste can be used for thermal energy recovery.

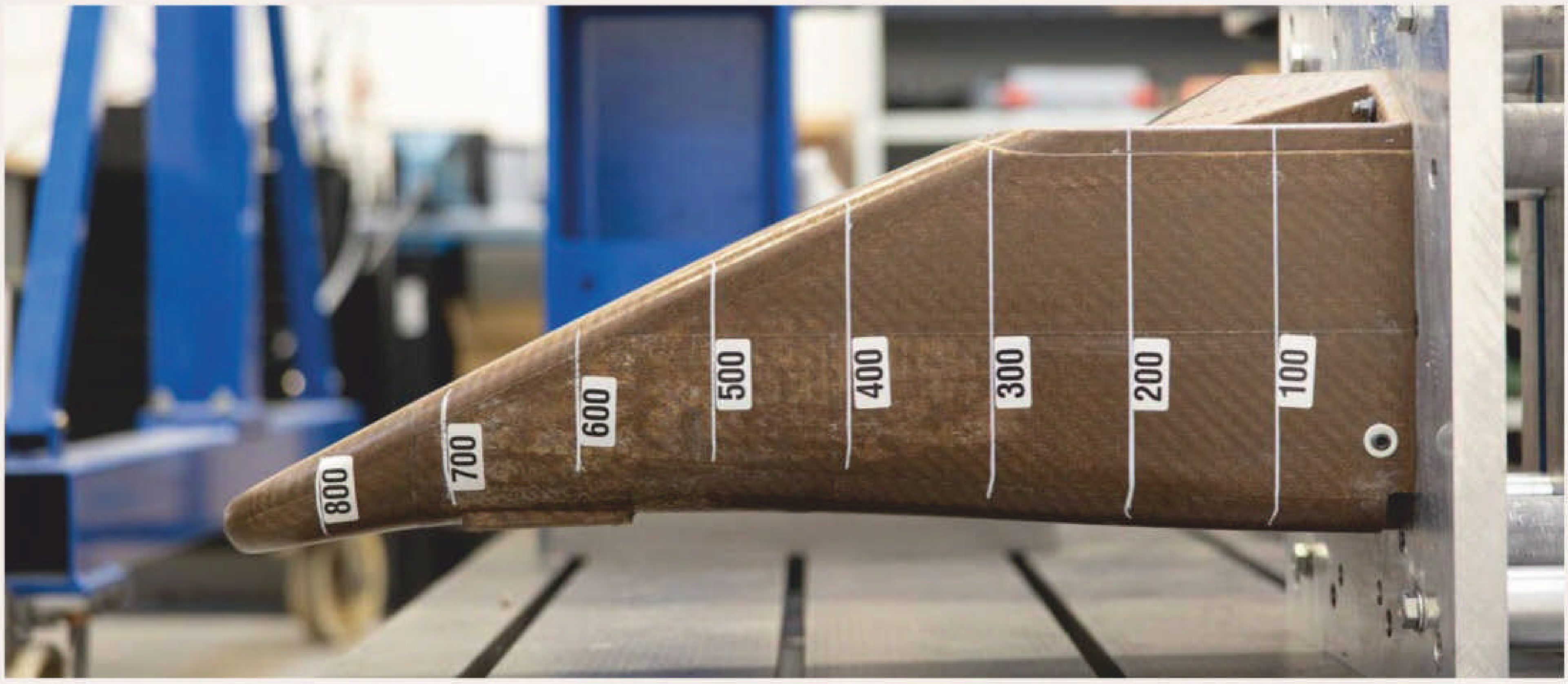
For the motorsports industry, this new research proves high performance natural fibres can be used for significantly wider applications than previously thought, reducing environmental impact and enabling technology transfer to mobility.

The natural fibre FIAS prototype designed as a proof of concept is currently around 40 per cent heavier than its carbon fibre counterpart, but enables a CO_2 reduction of approximately 50 per cent in the production process compared to the composite piece.

Pushing the adoption of natural fibres requires engineers to integrate it from the first day of the design phase,' says Mario Saccone, YCOM co-founder. 'Mastering the full process is the only way to optimise performance and increase the competitiveness of sustainable composite materials.

'We are really happy to collaborate with Bcomp in this development. Motorsport is a forge for new technology development, but this must be done fast and without any risk of error. YCOM has the experience to embark on complex R&D projects, with the flexibility of the motorsport approach to accelerate development.'

Under the new regulations, Formula 1 crash testing will move to a faster crash test speed, up from 15m/s to 17m/s, with a slightly increased mass



Still only at the development stage, the ampliTex flax fibre nosecone carries a significant weight disadvantage over carbon fibre, but a 50 per cent reduction in the CO_2 used in its production

However, with early crash test results on a par with those achieved with the carbon part, it is surely only a matter of time before that weight penalty is eliminated by racecar engineers

Another key area of development is the seat, as covered in *RE* V30N2. 'There used to be two levels of seat – advanced rally seat and competition seat,' says Watson. 'The rally seat has been in for 10 years now and is up for renewal. They are doing a static test for that. The competition seat was a dynamic test but now they are making both static tests. There are going to be more seats being tested.

'There is a misconception that the dynamic test is harder to pass but, if you look at accident data, the forces seen in a crash occur over a very short space of time. If that same force is applied for 30 seconds, it is much more significant.'

A further big change coming to racing in the short-to-medium term is alternative fuel technology. In particular, highly-pressurised hydrogen fuel cells. These will require a whole new way of testing, but Watson is not concerned as he runs a facility that caters for all walks of engineering, not only racing.

Safety service

'As long as it is safe, it will absorb the energy,' he says. 'That's the service we are providing. We are not dictating what the regulations are, or what we test. That comes from the FIA or relevant governing body. The engineering side is more interesting to me, and it really could be anything, from ambulance components to wheelchairs. It's the mechanics of it, and making sure we are providing a good test service.'

The ability to deliver the information has changed in 2020, thanks to the coronavirus pandemic. Before, testing would be witnessed by the team, Cranfield staff and officials from the relevant governing body. But with social distancing now a requirement, it has become a more remote process, with the high-speed camera footage, test results and analysis all sent back to headquarters digitally. If anything, this has improved the process at Cranfield, with fewer people on site.

'People are able to view the tests much closer via a tablet or Smartphone, so that has opened up a whole new way of working,' says Watson. 'It has reduced the number of people travelling to witness the tests.'

While the test facility at Cranfield has updated its working practices to cope with the pandemic, with the ever more stringent tests ahead for the next generation of Formula 1 cars, the Impact Centre has also upgraded its facilities to meet them. The drive for safer racecars continues.

In a spin

Revisiting the perennially complicated problem of tuning the differential

By **DANNY NOWLAN**

From a race engineering perspective, tuning the differential is a delicate balance between how much power you can put down and not scaring the one behind the wheel half to death

One of the most important, yet most often forgotten, set-up items in engineering a racecar is the differential. The reason it is so important is it plays a critical role in both power delivery and car handling. Ignore both at your peril.

A couple of years ago I addressed this matter at length, but recently received a great question on what your ballpark differential wheel speeds should be. That offered a perfect opportunity to re-visit this important chassis engineering topic.

The principal problem we have with the differential is we have two wheels moving at different speeds, as illustrated in **Figure 1**.

The reason tuning the differential is such a mess is that for a given forward speed, V, and a given yaw rate, r, because the wheels are separated by a track, t, we have the inside wheel velocity at V-t.r/2 and the outside wheel velocity at V+t.r/2.

Making an already tricky situation worse is the fact the differential was never truly engineered. It just sort of happened. As a consequence of this, there are many different types, including locked, open, Torsen and the many variants of our old friend, the limited slip differential.

Now, what also must be considered is the mid-corner condition in racing where both the inside and outside of the tyre have wildly different traction and cornering conditions. This is illustrated in **Figure 2**.

As can be seen from **Figure 2**, the traction circle radius is much greater on

Figure 1: An illustration of the inherent problem posed by the differential

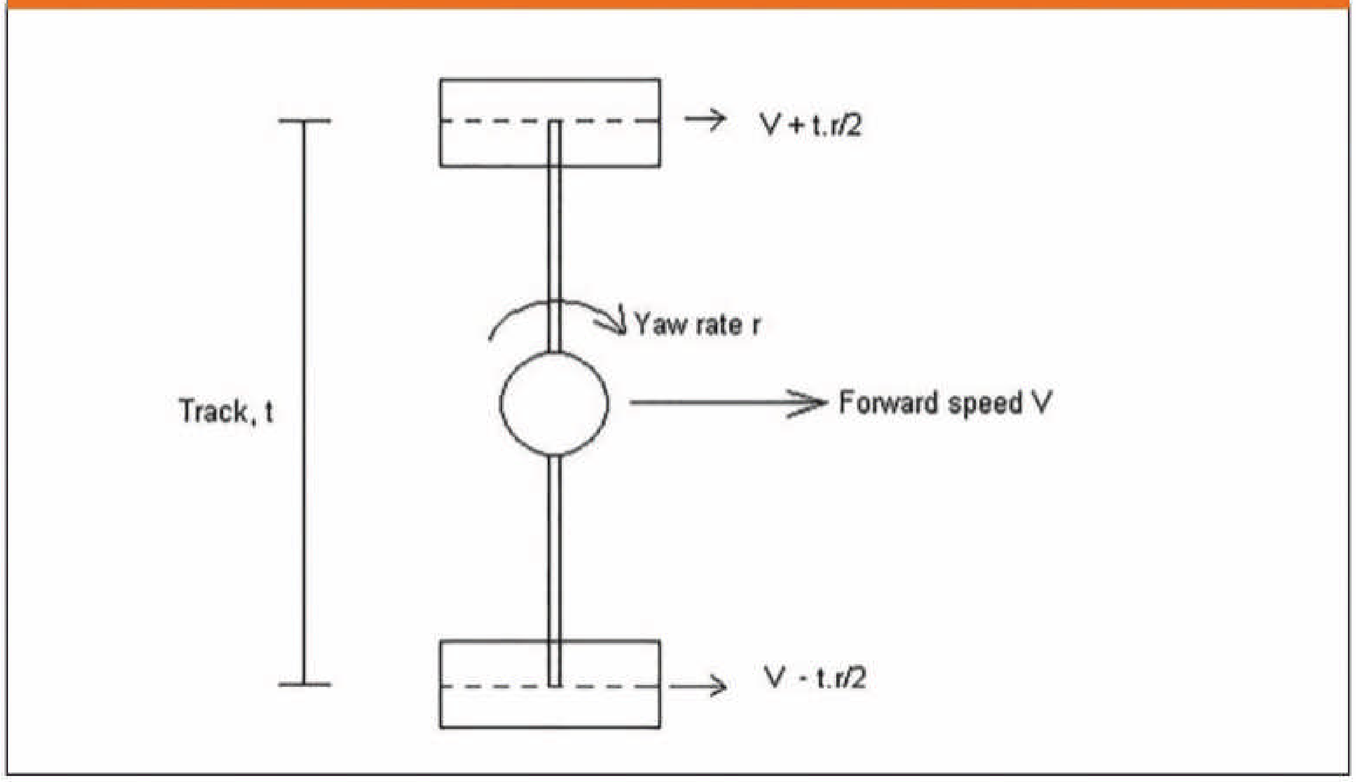
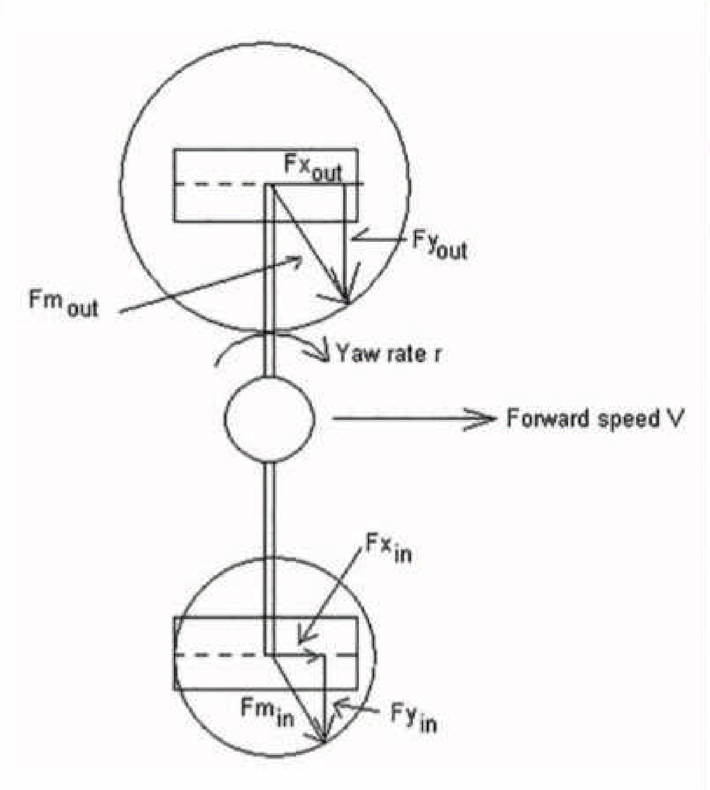


Figure 2: Traction circle conditions at the mid-corner situation



Making an already tricky situation worse is the fact the differential was never truly engineered. It just sort of happened

EQUATIONS

EQUATION 1

$$V_{Diff} = t \cdot r \approx \frac{t \cdot a_y}{V}$$

$$SR_{MAX} = \frac{V + t \cdot r / 2}{V - t \cdot r / 2} - 1$$

Where:
V_{Diff} = differential speed between the wheels
SR_{MAX} = maximum slip ratio of the inside tyre
V = current forward speed of the car (m/s)
r = current yaw rate (rad/s)
t = relevant track width
a_y = lateral acceleration (m/s²)

EQUATION 2

$$V_{IN\_MAX} = \left(V - t \cdot r / 2\right) \cdot \left(\frac{V + t \cdot r / 2}{V - t \cdot r / 2} - 1\right)$$

EQUATION 3

$$V_{Diff} = t \cdot r \approx \frac{t \cdot a_y}{V} = \frac{1.6 * 1.6 * 9.8}{30} = 0.836 m/s$$

$$SR_{MAX} = \frac{V + t \cdot r / 2}{V - t \cdot r / 2} - 1 = \frac{30 + 0.836/2}{30 - 0.836/2} - 1$$

EQUATION 4

$$F_{x\_in} = f(SR) \cdot Fm_{IN}$$

Where:
Fm_{in} = maximum possible tyre force for the inside tyre
F_{x_in} = Longitudinal force on the inside tyre
$f(SR)$ = Normalised slip ratio function bounded between zero and one

EQUATION 5

$$F_{x\_in} = f(SR_{OUT}) \cdot Fm_{OUT}$$

$$f(SR_{OUT}) = \frac{F_{x\_in}}{Fm_{OUT}}$$

Where:
Fm_{out} = maximum possible tyre force for the outside tyre
SR_{out} = slip ratio on the outside tyre

the outside tyre then it is on the inside tyre. So, if we apply exactly the same slip ratio to both the inside and outside tyre, the differential will turn the car quite forcefully. A driver of the calibre of the likes of Lewis Hamilton / Ayrton Senna / Michael Schumacher could probably handle this, but most racecar drivers won't.

Remembering the original question about what level of differential slip we should be aiming for, and applying a little bit of maths to **Figure 1**, we can deduce **Equation 1**. Working that through, our limiting case of the inside tyre will be as shown in **Equation 2**.

But here is where things start to become even more tricky. What will be the magnitude of VIN_MAX for a typical corner? Let's do a quick hand calculation for a typical racecar with the parameters shown in **Table 1**. Crunching the numbers, the results are seen in **Equation 3**.

This is actually very revealing. Mid-corner we are pulling maximum, or near maximum, slip angle. This is typically six degrees, or 0.1047 rad. Given that slip ratio and slip angle are directly interchangeable, this means at the mid-corner condition we typically want the tyre slip ratio to be about 10 per cent of the maximum slip angle. You can get that derivation from Miliken's tyre chapter on mixed slip conditions.

For what we have just calculated, we are not that far away from the 10 per cent maximum slip ratio condition, so we are going to leave that slip ratio as is. Yes, I accept we will be compromising the inside tyre a bit, but don't panic, we are not setting it on fire either.

Table 1: Typical corner parameters

Parameter	Value
Track	1.6m
Speed	108 km/h/30 m/s
Ay	1.6

Table 2: Maximum tyre force values

Parameter	Value
Fm_{in}	2000N
Fm_{out}	5000N
Max slip ratio	0.1047

Outside tyre slip

The next step in this process is what do we want the outside tyre slip to be. To find this out, we must first calculate the force being generated longitudinally by the inside tyre. A rough approximation of this is given in **Equation 4**.

The critical question here is what sort of slip ratios do we need on the outside tyre to match the required force on the inside tyre? This is outlined in **Equation 5**.

The balancing act between **Equations 3-5** will tell us where to go, not only in terms of differential speed front to rear but how you want to set up the differential. Now let's illustrate this with some numbers, see **Table 2**.

EQUATIONS

EQUATION 6

$$
\begin{aligned}
F_{x\_in} &= f(SR_{IN})\cdot Fm_{IN} \\
&= \frac{0.028}{0.1047}\cdot 2000 \\
&= 540N \\
f(SR_{OUT}) &= \frac{540N}{5000N} \\
&= 0.108 \\
SR_{out} &= 0.108 * 0.1047 \\
&= 0.0113
\end{aligned}
$$

EQUATION 7

$$
\begin{aligned}
r &= \frac{a_y}{V} = \frac{1.6*9.8}{30} = 0.52rad/s \\
V_{out} &= (V + t\cdot r/2)\cdot(1+SR_{OUT}) \\
&= (30 + 1.6*0.52/2)\cdot(1+0.0113) \\
&= 30.76m/s \\
V_{diff} &= V_{out} - V_{IN} \\
&= (V + t\cdot r/2)\cdot(1+SR_{OUT}) - (V - t\cdot r/2)\cdot(1+SR_{IN}) \\
&= 30.76 - (30 - 1.6*0.52/2)\cdot(1+0.028) \\
&= 0.35m/s
\end{aligned}
$$

EQUATION 8

$$
\begin{aligned}
F_{x\_out} &= f(SR_{OUT})\cdot Fm_{OUT} \\
&= \frac{0.028}{0.1047}\cdot 5000 \\
&= 1337.2N \\
\delta F &= \frac{F_{OUT} - F_{IN}}{2} \\
&= \frac{1337.5 - 540}{2} \\
&= 398.8N
\end{aligned}
$$

EQUATION 9

$$
LR = 100\cdot\frac{T_{SLOW} - T_{FAST}}{T_{TOTAL}}
$$

Where:

LR = locking ratio
T_{slow} = torque on the slower wheel
T_{fast} = torque on the faster wheel
T_{total} = total torque

EQUATION 10

$$
\begin{aligned}
LR &= 100\cdot\frac{T_{SLOW} - T_{FAST}}{T_{TOTAL}} \\
&= 100\cdot\frac{F_{out} - F_{IN}}{F_{out} + F_{IN}} \\
&= 100\cdot\frac{1337.5 - 540}{1337.5 + 540} \\
&= 42.5\%
\end{aligned}
$$

To make things simple, I'm going to assume a linear slope for function, f(SR), where zero is the value for no slip ratio and one is the value for the maximum slip ratio. Before you say it, I realise this is committing a litany of tyre modelling sins, but the whole point of this is to give you all some very simple examples so you can get a numerical handle on what the differential needs.

The other thing here is you need a good understanding of your tyres. Again, this is one of the great things about simulation since it forces you to understand the racecar before you question it. Bringing this all together and calculating out **Equation 5**, gives us **Equation 6**. This means that for equal forces, the wheel speed on the outside is given by **Equation 7**.

To ensure we have balanced forces, this means the outside wheel has to be going 0.35m/s or about 1.1 per cent faster than the inside wheel. Remember this achieves parity of forces. But now we must ask what is going to happen if we increase the outside rear wheel to a slip of, say, 0.028? Re-working **Equation 6** gives us **Equation 8**.

In this case, if we require both tyres to have the same slip ratio, the diff will have to produce a differential force of 398.8N.

To finish this discussion, figuring out the locking ratio of the differential is very easy. All we need to do is to recall our equation for the locking ratio, as shown in **Equation 9**.

Here, torque and forces are interchangeable. And since we are traction compromised, the input force here will be the sum of the inside and outside forces we have just calculated. Plugging in the numbers, we reach **Equation 10**.

As we can see, this is a pretty aggressive differential locking ratio, but we'll see how to deal with this shortly.

Number of the beast

The reason we have gone to all this trouble is so we can now specify numerically what a differential looks like. Recall at its most fundamental level, the differential transfer forces from the wheel that is spinning the most to the wheel that is spinning the least. This can be quantified by **Figure 3**.

At its most fundamental level, the differential transfers forces from the wheel that is spinning the most to the wheel that is spinning the least

The two horizontal axes in **Figure 3** are input force, which is the force coming from the engine and differential wheel speed. The z axis is the differential force that is applied to each wheel. In the example here, for an input force of 10,000N, at a differential wheel speed of 4m/s, the delta is 1000N.

The force differential is therefore 10,000/2-1000N for the wheel that is spinning the most, and 10,000/2+1000N to the wheel spinning the least.

This can also be illustrated via torque, but the bottom line is it means the same thing. What we have just done with this analysis, albeit highly simplified, is to give you the numerical tools to populate this graph via simple hand calculations.

That is powerful in itself, but your ace in the hole is refining it through simulation and the logged channels you get back from ChassisSim. One of the things ChassisSim logs is longitudinal force on each axle, which allows you to see what this can do to driveability. An example of this is presented below in **Figure 4**.

If you take a look at the plot in **Figure 4**, you'll see the logged channels, Force x RL and Force x RR. These are the longitudinal forces being applied at the contact patch. How you tune this is that you start with an open differential assumption and then put in your differential with the calculated locking ratio. Then, by looking at the steering trace comparison between the open differential and the locking ratio, you can adjust the locking ratio depending on what your driver can put up with. That is a perfect example of how to use hand calculations and simulation together.

Limitations

Our discussion would not be complete, however, if I didn't mention the limitations of what we have done. As I mentioned earlier, we have committed a number of tyre modelling sins in order to simplify this. The biggest is making a straight, linear function of the normalised slip angle curve. Where this will make its impact felt is with the specific slip ratios.

One thing we haven't covered is to assume maximum slip angle for the outside and rear tyre. However, if you look at Miliken's treatment of mixed slip conditions you'll find we are actually on very firm ground.

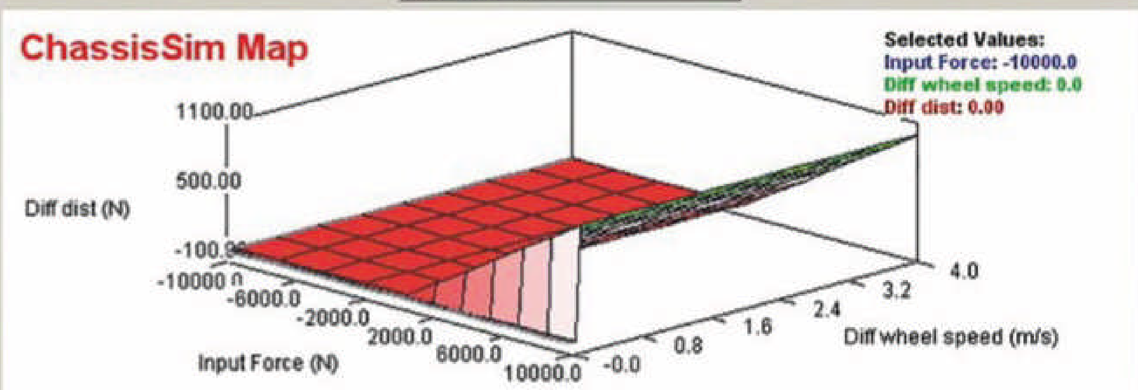
The other thing to bear in mind with this calculation, depending on the load transfer and yaw rate, is you are playing a delicate balancing act between how much power you can get down before freaking the driver out.

In closing then, while the differential poses challenges, there is a way through the jungle. We saw through the use of first principles and some hand calculations how you can begin to understand what the differential needs. But in order to do so, you need to have a firm handle on your tyres. This is where vehicle modelling comes in. While not perfect, it wasn't totally overbearing.

Then, once you have established your base settings, you can use simulation to tie everything together. It isn't a magic wand, but it does hopefully show you need not fear the racing differential.

Figure 3: Differential wheel speed force vs force distribution

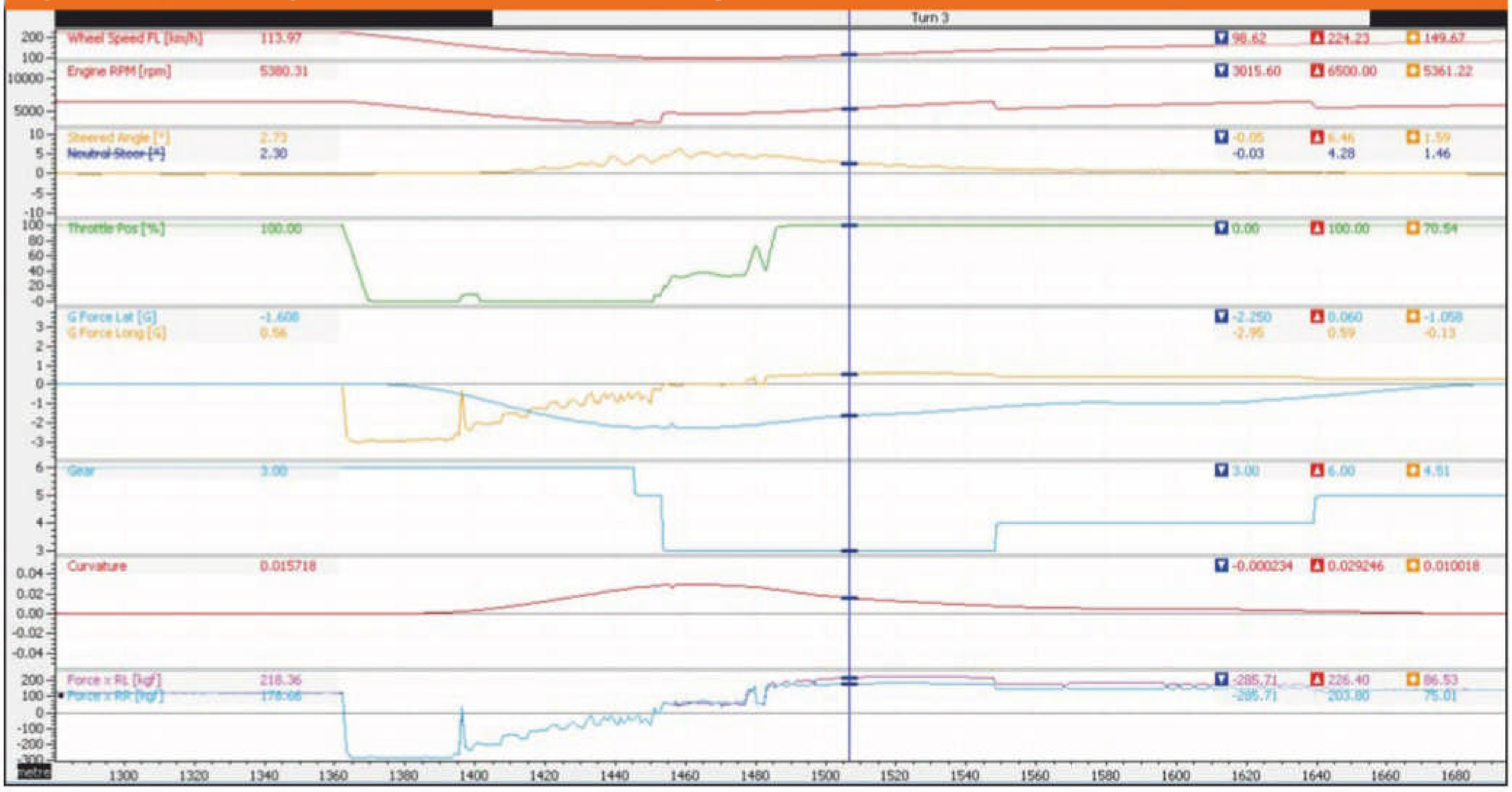
Rear Differential



	0.0	0.1	0.1	0.6	1.1	1.6	2.0	2.5	3.0	3.5	4.0
-10000.0	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-7500.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-5000.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-2500.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1666.7	0.00	0.00	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67	166.67
3333.3	0.00	0.00	333.33	333.33	333.33	333.33	333.33	333.33	333.33	333.33	333.33
5000.0	0.00	0.00	500.00	500.00	500.00	500.00	500.00	500.00	500.00	500.00	500.00
6666.7	0.00	0.00	666.67	666.67	666.67	666.67	666.67	666.67	666.67	666.67	666.67
8333.3	0.00	0.00	833.33	833.33	833.33	833.33	833.33	833.33	833.33	833.33	833.33
10000.0	0.00	0.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00

OK | Cancel | Axes Properties/Calculator | Export text/Aero File | Import text file

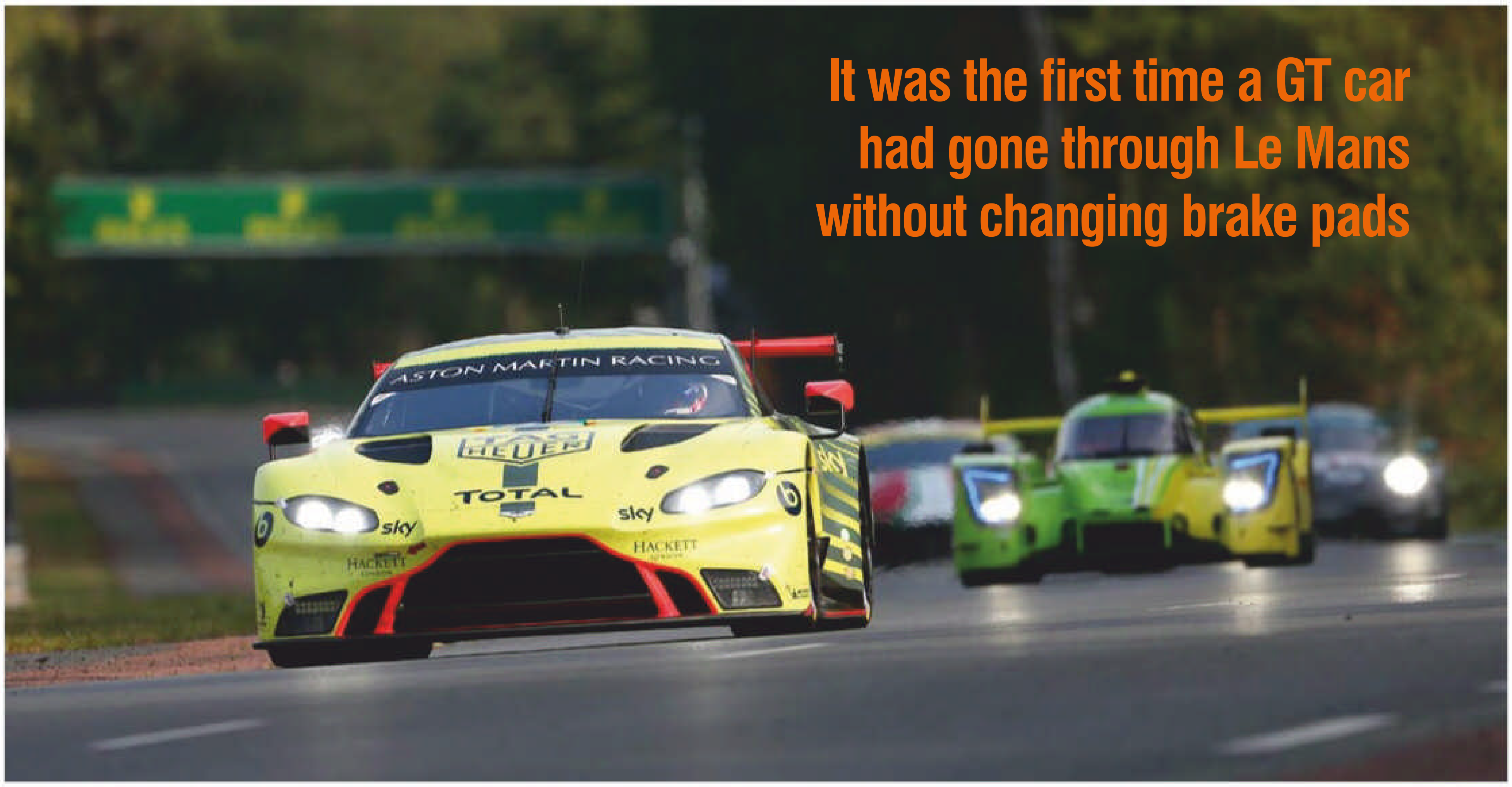
Figure 4: Plot of longitudinal forces for a limited slip differential



Endless summer

Japanese brake manufacturer sets new milestone in GT racing

By ANDREW COTTON



A three-day pre-event test at Motorland Aragon paid off when Aston Martin Racing achieved its goal of not having additional time on pit road for brake replacement at Le Mans

Aston Martin Racing's victory at Le Mans came down to a combination of circumstances. Having sorted out the handling at the rear to maintain the Michelin tyres through a double stint, and with a Balance of Performance that seemed on paper at least to help the Vantage GTE car, it was looking promising for the British team even before the green flag was flown.

What wasn't known was that the team was planning to complete the 24-hour race without changing brake pads, courtesy of an arduous three-day test at Motorland Aragon in the build up to the race.

With Covid restrictions, the team had only that one test to prepare for the race, and brake supplier, Endless, brought no fewer than 10 different pad combinations to try. This was typical of the brake manufacturer that has been supplying its product to British teams since the heyday of the British Touring Car Championship in the mid-1990s.

'We supplied the BTCC Volvos, Ford Mondeos and Hondas,' says Lucas Nylund, CEO of Endless Brake Technology Europe. 'In Japan, development is important, and we turned up [to the BTCC] with 30 different compounds for our pads. The engineers said that would give them a nightmare, but we explained that it's performance.'

Since then, Endless has gone on to supply factory teams in WRC, GT racing and, of course, the Mercedes Formula 1 team, winning World Championships along with way, but this event was special. It's the first time a GT car had gone through Le Mans without changing brake pads. Not only that, the drivers did not even have to change braking habits throughout the race.

Maximum performance

'It was fantastic, and a very successful development,' confirms Nylund. 'You can go to the maximum performance without taking extra care of the brakes.'

The company had completed 24-hour races without changing brakes before, notably at the Nürburgring, but there braking requirements are very different to Le Mans, with only a few big stops required on the Nordschleife. Le Mans is much harder on brakes, so this was a far bigger challenge.

Part of the success came from the development facility in Japan, where a new full-size dyno was introduced at the tail end of 2019, capable of testing brakes from up to 300km/h. This is the third dyno developed by Endless and possibly the company's most important advance to date.

'This is performance, and if you can gain lap time by braking later then it is an advantage,' states Nylund. 'If you can be 1-1.5 second faster per lap on the brakes, and then apply that to an endurance race, it is an advantage of minutes. From that, we can work to tailor make pads for our customers. AMR was a special development pad, and their targets were very clear from the start.'

The company is now analysing why, at the final round of the WEC in Bahrain in November, the Aston Martins had to change brakes during an eight-hour race. The circuit is known to be particularly hard on brakes, and the team and brake supplier didn't have time to test ahead of the final race, but Nylund admits 'it's a pain. Bahrain you normally have pad problems, and there is a lot of lifting and coasting there, but it is clear that next year we will need a Bahrain-specific pad.'

For now, though, having won Le Mans without a brake change, completing the race without a pad change is likely to become normal practice in the future.

Champions

The 2020 season has been unusual in many ways but, even in the midst of uncertainty, racing companies have continued to provide products that enabled teams to compete on national and international levels. *Racecar Engineering* salutes those who have once again provided engineering excellence to the world of motor racing, and we congratulate the following companies on their achievements this year.

AUSTRALIAN V8 • BTCC • DTM • FORMULA 1 • FORMULA E • GT


Jakob Ebrey

Laser Tools Racing won the British Touring Car Championship with Ash Sutton

Team Techeetah won the FIA Formula E title


XPB

Rene Rast and Audi took another DTM title together


SRO/Kevin Pecks

Audi Sport Team WRT was champion in the GT World Challenge overall with the Audi R8


XPB

Mercedes took its seventh Formula 1 title with Lewis Hamilton


Jake Galstad

Acura again won IMSA's DPi category with Penske Racing

ARk Racing

ARP automotive Racing products

ATL Aero Tec Laboratories Ltd

Bcomp

Breda Racing racing components and equipment

Primary Designs

Pyromeral Systems

Renvale harnessing | sensors | design

SHD composites advanced composite materials

Special Ops Ltd elite design & manufacturing specialists

# of 2020

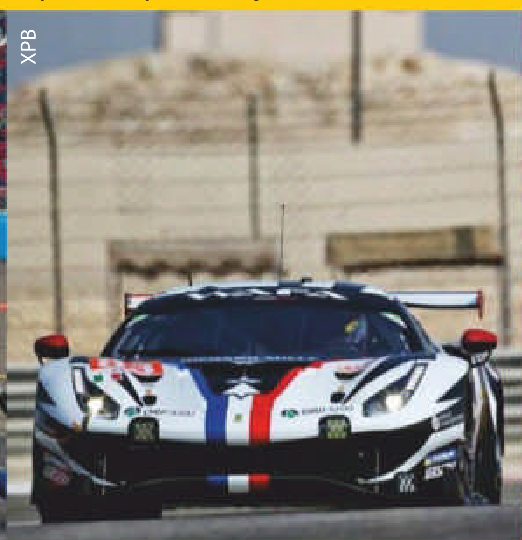
WORLD CHALLENGE • IMSA • INDYCAR • NASCAR • WEC • WTCR

Scott Dixon again dominated IndyCar, taking his seventh title for CGR

Lynk&Co Cyan Racing's 03 TCR was the best of the International TCR series

Getty

Chase Elliott was a popular NASCAR champion for Hendrick Motorsport

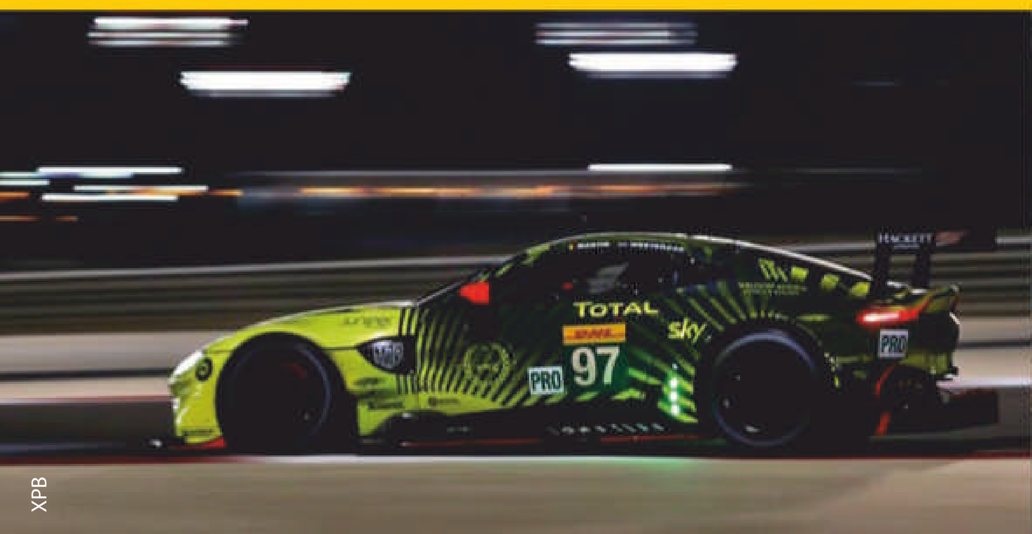


XPB

AF Corse won the WEC GTE Am class

XPB

Toyota completed a WEC hat trick



XPB

Aston Martin Racing took WEC GTE-Pro honours in 2020

XPM

United Autosport won Le Mans and the WEC LMP2 title

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Safe haven

Reflections on racing's response to the strangest of years

One bumper weekend in November saw the conclusion of the fight for Formula 1's drivers' title, IMSA, the GT World Challenge Europe and the FIA World Endurance Championship. It wasn't that long ago that NASCAR, IndyCar and the Australian V8 series all declared their champions either.

In a truncated season, such as 2020 has been, it was inevitable the series should all come to a grinding conclusion at a similar time. But what the teams, suppliers, manufacturers and organisations have achieved to bring the season this far in such circumstances, not to mention the print, digital and television media, is little short of extraordinary.

At the start of the pandemic, companies rose to the medical challenge and helped to deliver a staggering number of breathing apparatus designed to help those suffering in hospitals, and to help those treating the patients in the most horrific of circumstances.

Then, when it became clear racing could continue, schedules were re-jigged for the race weekends and teams had to make do with the limited testing available given travel and time restrictions. Suppliers, meanwhile, had to cope with reduced hours and new ways of working, while still developing and delivering their product to the teams for competition.

Once racing got back underway, regular Covid testing for all staff within the paddock made it probably the safest place to be. Certainly, that felt to be the case when I attended the Le Mans and Spa 24-hour races. At both, the knowledge that everyone had tested negative before they collected their passes, that temperature checks were being taken entering the circuit daily, social distancing rigorously enforced and mask wearing on site compulsory made life palatable.

It was different in Formula 1, where the print media were not given access to the paddock at all, replaced at the Turkish Grand Prix by a giant cuddly toy. It reminds me of a race where the media were banned from the pit lane, but the president of the FIA turned up on pit road accompanied by a scantily-clad model on roller skates.

What has become apparent is the discrepancy between countries in their approach to the pandemic. Some, such as Australia, have effectively shut their borders, making international racing almost impossible. Others, such as Hong Kong and Macau, have implemented long quarantine periods, which has made the organisation of races rather more challenging.

Even in Europe, regulations are different from country to country. Germany has provided access to testing, and has a relatively free population with low infection rate. The UK, by contrast, severely limited access to testing throughout the season, implemented a blanket 14-day quarantine period for those travelling and still had the highest infection rate in Europe.

Willing sacrifice

What was clear throughout the year, though, was the sacrifice team members and media were willing to make. Those required to quarantine did so. Others, particularly those who raced in the US, chose to stay there. A shortened schedule increased the pressure on teams and reduced time between events anyway, but there was also the desire *not* to travel unnecessarily. At the end of the season, given the number of racing personnel undertaking international travel, there were remarkably few cases of Covid-19 among the racing fraternity.

It has to be said that motorsport rose up and delivered on a global platform

This, of course, does not mean the case has been overblown and the measures put in place by governments all over the world were not necessary. On the contrary, the increased measures implemented, and pretty much obeyed by all, meant the racing community protected itself remarkably well.

Social distancing in the paddock meant the regular haunts for coffee were no longer allowed, which made getting through long races challenging. For the Spa 24-hours, I took my own coffee machine just in case. The downside to the restrictions at Spa was that Lamborghini's version of a 'bubble' – a champagne reception on Saturday night for teams, drivers and guests – had to be cancelled because Belgium mandated no sale of alcohol on site, and backed that up with law enforcement officers in the hospitality unit.

Despite the restrictions, and despite the challenges, it has to be said that motorsport rose up and delivered on a global platform. We all hope next year will see a vaccine and return to normality, with the fans back and travel restrictions lifted, but we should look back on this difficult year with pride.

ANDREW COTTON Editor