F1 TECHNOLOGY: Peter Wright on the future of manufacturer racing

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McLaren MCL35

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Audi announced in November the end of its Formula E programme following season seven to focus on pastures new

Schedule overload

Is F1 at risk of burning out the brains the revolution will rely upon?

There are going to be 23 Formula 1 races in 2021. That is a lot of travelling, a lot of being away from home and a lot of work for the F1 personnel.

A few years ago I was doing the Le Mans Series, the American Le Mans Series and the 24 Hours of Le Mans itself, which worked out at a similar number of races. What did I learn? Well, I learnt that it's not particularly healthy.

The schedule ran from January to December that year and it was a killer. We were either in Europe or flying back and forth to the US, and to do those long-haul flights every couple of weeks was really tough. The F1 teams will be going from one event to the next and not going home in between some of them, which I'm sure will take its toll.

The alternative is to have much bigger teams so each person doesn't have to do all 23 races. This is actually easier said than done as these are specialist roles and it will, of course, increase costs.

Money maker

Is it necessary? Do series really need that many races to survive? One GT team owner said if a team is making money at the races, put as many as you like on the schedule, but if they are losing money then do as few as possible.

The F1 teams are clearly making the money. Alpha Tauri has said it needs the events in order to be able to capitalise on what it has invested, which makes sense.

The elephant in the room, though, is still Covid-19. The virus isn't going to go away on December 31. Formula 1 has done a good job of handling the pandemic in 2020, but there is always the risk of losing some staff to a positive Covid test. As a team, if a positive test prevents your team competing at an event, that will cost both points and money.

Teams are now taking calculated risks by travelling to races with revised calendars that have required lot of thought to keep championships viable. But does that mean so many events that work-life balance is sacrificed? I don't know the answer to that, but maybe I'm getting old and my preference for gardening rather than travelling might be a bit out of touch.

At the time I was taking part in two series, I was up for it, but I'm less convinced of the merits of burning the proverbial candle at both ends these days. F1 has already mentioned the use of B teams to make such an intense season work, but that instantly adds cost. Cost that was just saved by restricting team numbers and eradicating test teams.

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More races, more money, but can the personnel on the ground take the increase in number of events?

As an observer, it's difficult to comment confidently on the proposals. Perhaps the teams themselves feel it's a sacrifice they are willing to make without there being big repercussions, but only time will tell.

Nine months since Europe went into lockdown – longer for countries in Asia – a good number of places are not back to what they would call normality, but there have been some incredible scientific advances to bring us closer to what we once knew. Racing, like all sports, has provided some escapism during this difficult time and, even if fans haven't been able to attend races, live streaming has really come into its own and helped the sport reach new fans. It's been a big positive at a time when people are struggling mentally to adjust and reconcile with the situation they find themselves in.

Racing inspired me to continue my ambition to study engineering and I see a parallel in this situation. I am passionate about promoting engineering and science to the next generation and, as this pandemic has shown, science has advanced and been pivotal in policy making and vaccine development. I hope that racing, and how it has adapted to new protocols, as well as the flexibility of the business to meet health needs, can inspire people to investigate STEM subjects and maybe study them. There's a lot of development and inspiration that comes off the back of what we do, which sometimes we may take for granted.

New minds

In the UK, the government recently announced that by 2030, sales of petrol and diesel cars will be banned, no doubt influenced by the movement to question our sustainability. Easy to say. But for this revolution to happen, an entire infrastructure needs to be put in place, which needs creative thinking from new minds. Questioning how we are operating now and seeing a new future driven by science is the only way we can adapt, and I hope younger people will have an appetite for this and want to be a part of the movement, then do something about it.

Motorsport and the FIA stand at a junction where racing with different powertrains can become a supporting tool to progress. Racing may play a small or a big part in the future of mobility, but it has much wider reaches if it brings science a little closer to the next generation. I just hope everyone isn't too worn out to do the work!

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

For this revolution to happen, an entire infrastructure needs to be put in place, which needs creative thinking from new minds

Adjustments needed

Something has to be done, or allowed, to solve the F1 tyre problem

A problem needs action in order to solve it, or to at least to alleviate its effects. The constant critical issue of Pirelli tyre management creates massive headaches for drivers and engineers alike. This has required huge amounts of effort to combat, and led to Mercedes inventing its controversial DAS steering system. However, a relatively simple mechanical aid could be adopted that I suggest would certainly help. It's been around for more than 40 years and, guess what, it's the driver-adjustable anti-roll (sway) bar. Ideally fitted front and rear, such devices would allow drivers to assist in controlling tyre temperatures and degradation and balancing the handling of the car as it alters through a stint – especially if conditions change drastically.

Operated without external input and *adding* to driver skills, it seems little different than having brake bias and diff' settings adjustable, as currently permitted. A similar rotary dial on the steering wheel would do the job. I'm aware that anti-roll bars are way more sophisticated these days and packaging is a nightmare, but F1's clever engineers could cope with that, if the benefits were considered worthwhile.

Even just adjusting the roll rate at one end of the car would contribute to easing the seemingly unsolvable (by Pirelli, anyway) tyre problems.

Given that I criticise the grossness of current hybrid F1 cars, the idea of adding further weight may seem contrary, but that's easily solved by removing some of the multitude of non-essential sensors and associated kit, in favour of an FIA-mandated data acquisition package.

Double whammy

A similar decision was made some time ago with the single-source ECUs. I make no excuse for repeatedly promoting this to reduce the advantage of teams with greater backing. Despite the cost cap, they will otherwise still be able to devote more resource to performance analysis. Therefore, a positive double whammy.

I know, I know. For the same reason DAS was banned, this is to some extent controlling the suspension while the car is moving, which I guess is why driver-adjustable ARBs were first banned.

Relax the rule on this and what will be next, some might say? Driver-controlled dampers and torsion bars, ride height / rake adjusters? A fair argument, sure but, after the DAS steering affair the regulation makers should be sufficiently aware of possible loopholes to avoid any 'mission creep'.

Force majeure situations call for *force majeure* action. Until Pirelli can come up with better F1 tyres, I don't see why such a simple solution can't be implemented. From 2022, at least?

Aside from the overall picture, the decisions some F1 teams make can be puzzling, on the surface anyway. Like why Haas F1 has taken on Ferrari's head of chassis engineering, Simone Resta, in a senior position, while admitting it hasn't yet worked out what his role will be.

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Interesting moves: Mick Schumacher in the hot seat at Haas during the young driver test post Abu Dhabi Grand Prix

Normally, surely, one would identify a role requirement first and then recruit an appropriate person to fill it. Guenther Steiner has openly stated it has nothing to do with Mick Schumacher joining the team, but who is he kidding? Ferrari has a lot invested in 'Little Schu', in more ways than one. In placing him at Haas, they need to ensure a radical improvement in the US team's currently dismal performances.

Considering Haas' best year so far was the first one, without a database from previous seasons to lean on, it is clear that, unfortunately, its engineering has let it down badly ever since, given its drivers have remained the same.

As far as one can assess, the team lacks anyone who can strongly direct the car design and development technically. The team's main technical man, Ayao Komatsu, is by his own description primarily in charge of organisation, coordinating the drivers' groups of engineers and handling data. Perhaps Haas reasoned that with its unique, and innovative, structure of outsourcing almost everything to do with the manufacture and, effectively, the design of the car between Ferrari, Dallara and various others, it didn't need anyone in house to strongly direct and engineer the overall design and development. But an orchestra without a conductor is liable to miscue the music.

As I have commented before, I know from personal experience that such a dissipation of resources is inefficient, even with the sophisticated communication channels we now possess. Engineers and production people just being in different buildings a few miles apart – let alone in different continents and time zones – causes lapses in exchange of information, with consequent errors and misunderstandings. It undermines teamwork. While it's a great strategy for starting up, I don't believe it's a viable way forward in such a super-competitive environment.

American asset

Gene Haas' team is a great asset to F1. Apart from the fact it adds to the grid, having an American team involved is extremely important to Liberty's aims of more US races, and also for diversity in the premier motor racing championship. Haas' commitment should be applauded and, together with all of his team, he deserves better reward.

On the plus side, despite nostalgia for the 'family'-owned F1 team concept of yesteryear, heartening news is large-scale corporate investment in McLaren. Following similar financial input into Williams and Racing Point, even during a pandemic, this surely indicates the fundamental value of F1, which has shown itself outstanding during this crisis. *Chapeau!*

PS Joni Mitchell famously sang 'You don't know what you've got 'til it's gone.' *Cue Alonso hustling the screaming, agile, V10-powered 2005 Renault R25 around Abu Dhabi circuit before the final 2020 GP. Fabulous. I bet there wasn't a single driver watching who didn't want to have a go in it.*

Even just adjusting the roll rate at one end of the car would contribute to easing the seemingly unsolvable (by Pirelli anyway) tyre problems

McLaren celebrates as Carlos Sainz Jr crosses the finish line in Abu Dhabi in his McLaren MCL35 to secure McLaren Renault third place in the constructors' championship

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Game of inches

The devil is in the detail when it comes to engineering for success in Formula 1

By STEWART MITCHELL

'Game of inches' is a famous phrase attributed to Green Bay Packers American Football team coach, Vince Lombardi, immortalised by Al Pacino in the film *Any Given Sunday*.

A 'game of inches' justifies why the smallest detail matters. Like American Football, Formula 1 is, too, a game of inches, as the difference between raising a championship banner and being considered a failure is often the smallest margin.

Although in contemporary Formula 1 Mercedes' domination seems insurmountable, the margins in 2020 have been tighter than many years before, with outright performance of all 20 cars on the grid falling within a delta of around 3.4 per cent between the best and worst. Some teams in the so-called midfield fall within less than 0.75 per cent of their closest rivals. As such, should a team's nominal performance fall to 99.24 per cent of its target pace, there's another team there to take advantage of that infinitesimally small error.

And such was the fortune of the McLaren Renault team who, at the very last race of the season in Abu Dhabi, clinched third place in the constructors' championship, beating Racing Point BWT Mercedes by just seven points. The battle for this position behind world champions, Mercedes Petronas AMG, and Red Bull Racing Honda has been one hard fought for the entirety of the 2020 season.

McLaren Renault's apparent game of inches approach has been well documented in 2020, that being a step away from where they were just a few years ago.

Starting gate

When it comes to the design philosophy of contemporary Formula 1 cars, the road the Mercedes Grand Prix team took a few years ago has become more of a highway with many other teams on the grid adopting Mercedes-developed concepts. The most extreme interpretation of this is the 2020 Racing Point BWT Mercedes, which appeared to be a 2019 Mercedes W10 outfitted with the BWT livery. However, Racing point was not the only one to take note of designs pioneered by the Brackley outfit. Renault, McLaren and Red Bull Racing are also adopting some of the master's black suit in 2020.

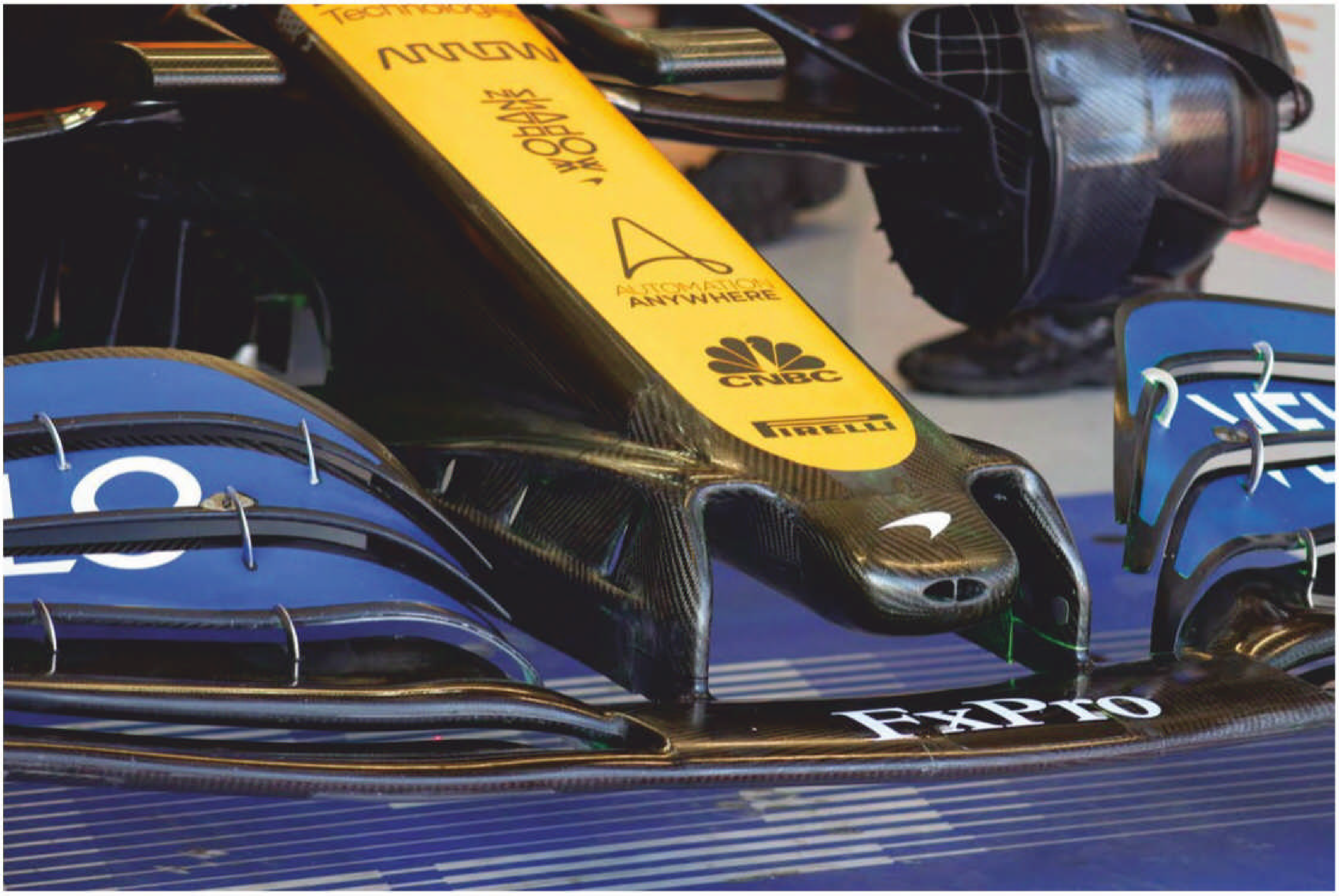
Of course, taking any one element of a racecar in isolation will not yield the same overall performance, as all parts of Formula 1 cars are intrinsically interrelated. Though throughout the paddock, the narrow nose pioneered by Mercedes a few years back seems to have found itself on a number of different cars, each claiming differing reasons for adopting such a solution. Additionally, the mid-height side impact structures, and the consequential high radiator inlets, have also been adopted throughout the paddock.

'One of our targets is to get to the front, but that's a huge step compared to where we are now. To do that in a year would be very welcome'

James Key, technical director, McLaren Renault

The McLaren MCL35 adopted a narrow nose from the offset in 2020 and brought another, more extreme, version of it later on in the season. The aerodynamic concept of the MCL35 is independent of many of its rivals, seeing a flatter riding car than a lot of its midfield competitors, while also producing devastating high-speed cornering ability over and above its closest rivals.

At the beginning of the season, James Key, technical director of McLaren Renault, explained the philosophy: 'One of our targets



Stewart Mitchell

The MCL35's narrow nose design, a philosophy pioneered by Mercedes a few seasons ago, appeared at the first outing for the car at winter testing in Barcelona

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The mid-height side impact structure concept was also adopted by McLaren for its MCL35

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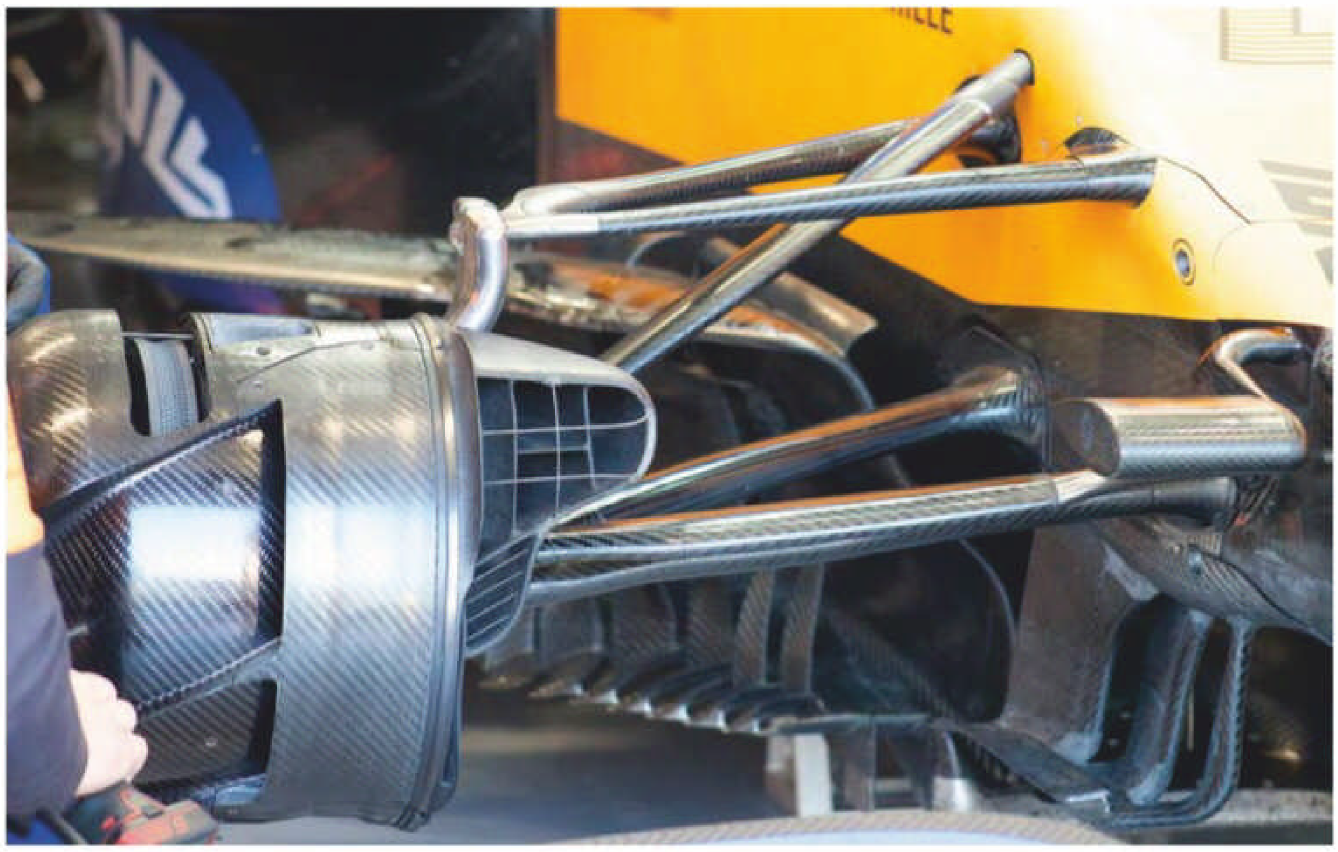
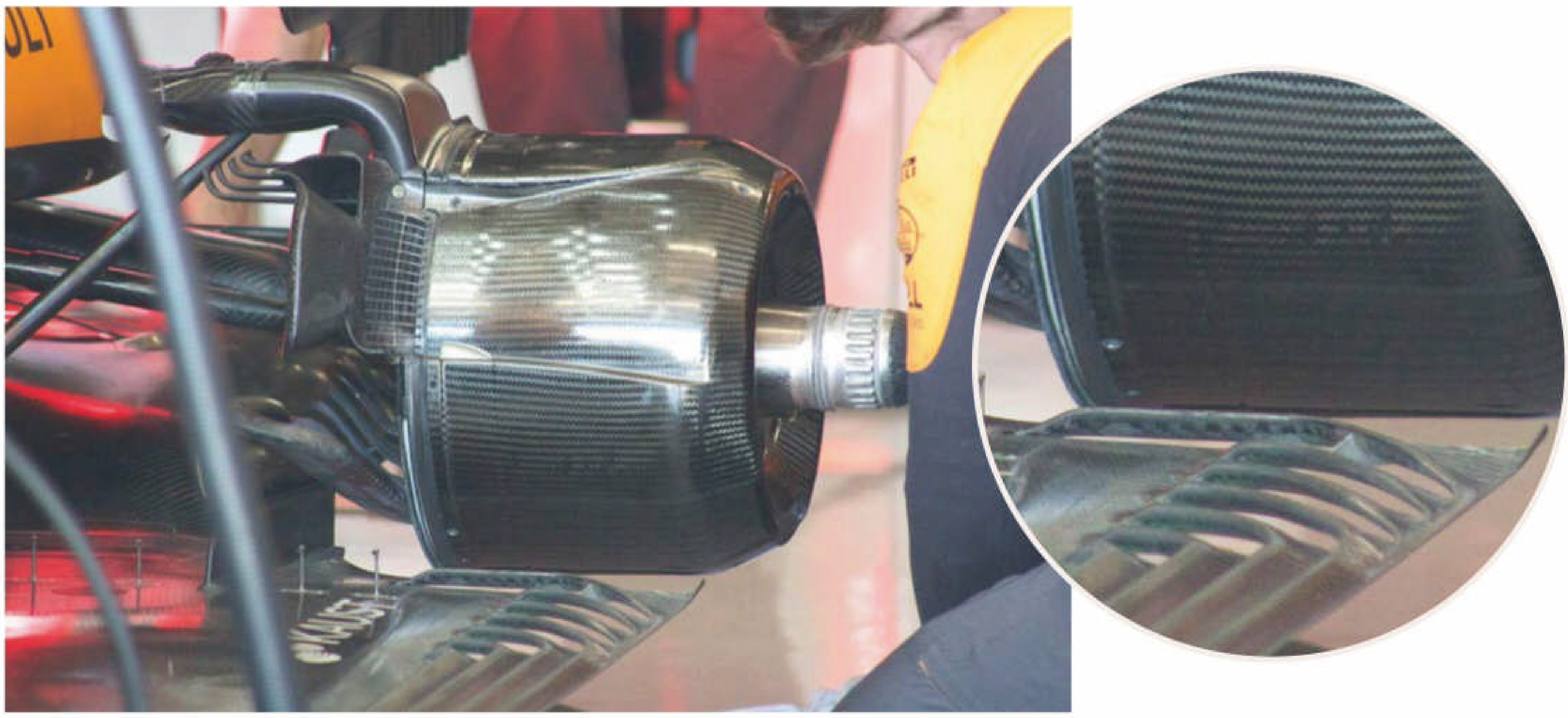


Front suspension design, however, was completely new for the MCL35

Stewart Mitchell



McLaren's new rear suspension concept for the MCL35. The complex rear floor aero structures will be simplified for 2021

is to get to the front, but that's a huge step compared to where we are now. To do that in a year would be very welcome.

'There were certain targets based on what we learned last year, where we found our weaknesses, that we really wanted to address. We could see some of those weaknesses were quite similar across the teams we were competing with, so we've been looking closely at those kinds of areas, and we have made some progress there.'

Areas of development

During the 2019 season, McLaren identified some areas of development outside of the scope available to bring them into immediate play. Limitations such as the existing suspension geometry meant these changes were destined only for the MCL35. The interim suspension changes made around the front and rear between 2019 and 2020 were triggered by architectural changes made between MCL34 and MCL35. These were predominantly designed to open up new avenues for exploiting aerodynamics in different ways but also enabled some vehicle dynamics changes as well.

'The changes did appear to work, though we did have to make these decisions early, so we were a little bit speculative,' admits Key. 'We did certainly get some positives in the rear suspension, which was quite different from last year.'

On the front suspension, Key says, 'By and large, we haven't had any big concerns as the suspension-associated developments brought to the car did what they needed to do, so we're quite happy with that. It gives us a base we're quite comfortable with going into next year, now that that's going to be homologated.'

McLaren's gearbox saw similar treatment to match the philosophy going into 2020, which coincides with significant changes made to the rear suspension. Conceptually, from the cockpit backwards, the McLaren MCL35 is a significant departure from its predecessor. The bodywork follows the trend throughout the paddock of a very narrow sidepod, which Key describes as, 'quite an exercise in packaging,' continuing, 'you have to plan early for that sort of thing, because it involves the engine installation and so on.'

'It all comes back to the complexity of the cars, because they are aerodynamic platforms above all and a dynamic platform that operates in an evolving environment'

Andrea Stella, McLaren Renault racing director

Power unit

Unlike many of the aerodynamic concepts seen on current Formula 1 cars, power unit design has seen a split in philosophies since the beginning of the hybrid era, each proving to have its benefits and disadvantages.

Half of the manufacturers have the compressor front mounted, which is the approach used by Honda and Mercedes, while the others have it rear mounted. It is understood that front mounting the compressor has its challenges on packaging in that area of the car, given it's more congested than the Ferrari or Renault engine from a chassis point of view. However, it makes it easier to package certain other elements. The Mercedes and Honda units are tightly designed, but each has volumes in certain areas the Renault and Ferrari don't, which each of the teams running them must account for.

Much of the development focus in Formula 1 today is to do with the MGU-K, which is connected to the crankshaft of the internal combustion engine and is capable of recovering or providing additional power (limited to 120kW or 160bhp by the rules). Under braking, the MGU-K operates as a generator to slow the car, reducing heat dissipated into the brakes and recovering some of the kinetic energy and converting it into electricity. Under acceleration, the MGU-K is powered from the Energy Store and / or the MGU-H and acts as a motor to propel the car.

Power unit development for all of the four current suppliers has been ongoing behind the scenes, though deployment of spec changes was capped in 2020, with the FIA announcing a bulk restriction on incremental updates to the PUs. Renault noted it would not update its PU through the 2020 Formula 1 season after opting not to bring a new specification to Austria in a bid to cut costs. Clearly, small changes made over the winter yielded performance for its factory team, and McLaren.

With Formula 1 being an energy limited formula, much of the focus in PU development has been in the MGU-K, which can result in a very digital feeling power deployment that can be difficult to manage. However, the Renault power delivery maintains good driveability, according to McLaren's racing director, Andrea Stella: 'The power unit has been improved, but it hasn't changed fundamentally, and the characteristics haven't changed.'

As for engine performance, and the freeze brought in by the FIA this season,

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The nose and sidepod design were heavily revised throughout 2020. Here is how the MCL35 appeared with its aerodynamic upgrades at the final race of the season in Abu Dhabi

McLaren's engine supplier, Renault's, team principal, Cyril Abiteboul, remains adamant: 'We are ready for some sort of compromise, in particular in the engine freeze because we accept convergence is happening, so spending big money is crazy.

'Having said that, there is clearly a line. We will not turn our backs on 70 years of competition on engines, engine development and performance. For us, the engine as a performance differentiator is at the core of Formula 1, it's what it means for us. We will not cross that line, that is very clear.'

Development in 2020

With 2020 such an unexpectedly compressed season, development presented a particular challenge for all teams in Formula 1, as Key highlights: 'It was particularly difficult this year, on the basis that we had lots of races in a very short time period, so bringing things to the track, testing them, taking the time to step back and look at the analysis and that sort of thing was quite different this year. We had to do all things in a compressed time scale, and also had homologation dates we needed to work to as well.

'That heavily influenced what we needed to do, given it wasn't a normal situation of introducing updates. We had to go through a rushed process and didn't have much time to step back and think was everything working or are we missing something? In certain areas we were missing something, so we backtracked a bit on certain developments, but the vast majority of development was sustained with the car.'

The most significant performance enabling development was a new nose, introduced at the Mugello round of the championship, and a package of related aerodynamic upgrades behind it that arrived in the subsequent rounds.

'The narrow nose we introduced had to be run and on the car by the end of September, due to an FIA-introduced homologation deadline,' confirms Key.

'After Nürburgring, we nailed down the spec of the car from that point forwards. The new elements performed as expected and we developed the car from there. Since then, there have been some additional development items based around that configuration.

'It took time because it was complicated – there was the front wing, barge boards and all these really complex bits involved, along with very short time scales and homologation all pushing you to make decisions by a deadline, which is not normal for development processing here.'

As for their on-track performance, Stella praised the drivers' feedback and understanding of the car, noting: 'In general, I would say even for a given specification of a car, and a given specification of tyres, the optimisation of a Formula 1 car is so complex that it leaves quite a lot of space to still be a pure exercise of engineering optimisation. Here, if you do your due diligence in terms of simulation, data analysis and looking at previous references but then don't fully exploit the package, you're going to be left behind.

'In a situation like we have this year, with five cars within a couple of tenths on nominal performance, if you don't maximise the package you're going to be at the back of this group of cars, which could mean you are out of Q3, and possibly out of the points.

'It all comes back to the complexity of the cars, because they are aerodynamic platforms above all and a dynamic platform that operates in an evolving environment.'

Driver performance

'Driver optimisation is critical as well. This year more than other years we saw a significant split in driver performance within the same teams. However, McLaren minimised this because Carlos and Lando have always been quite close to each other. There are some reasons for this that are not only technical.

'2020 really required us to have a good collaboration in terms of introducing new parts and managing parts for data evaluation, which takes time away from the normal preparation for a race week. Also, this year we had some new tracks.

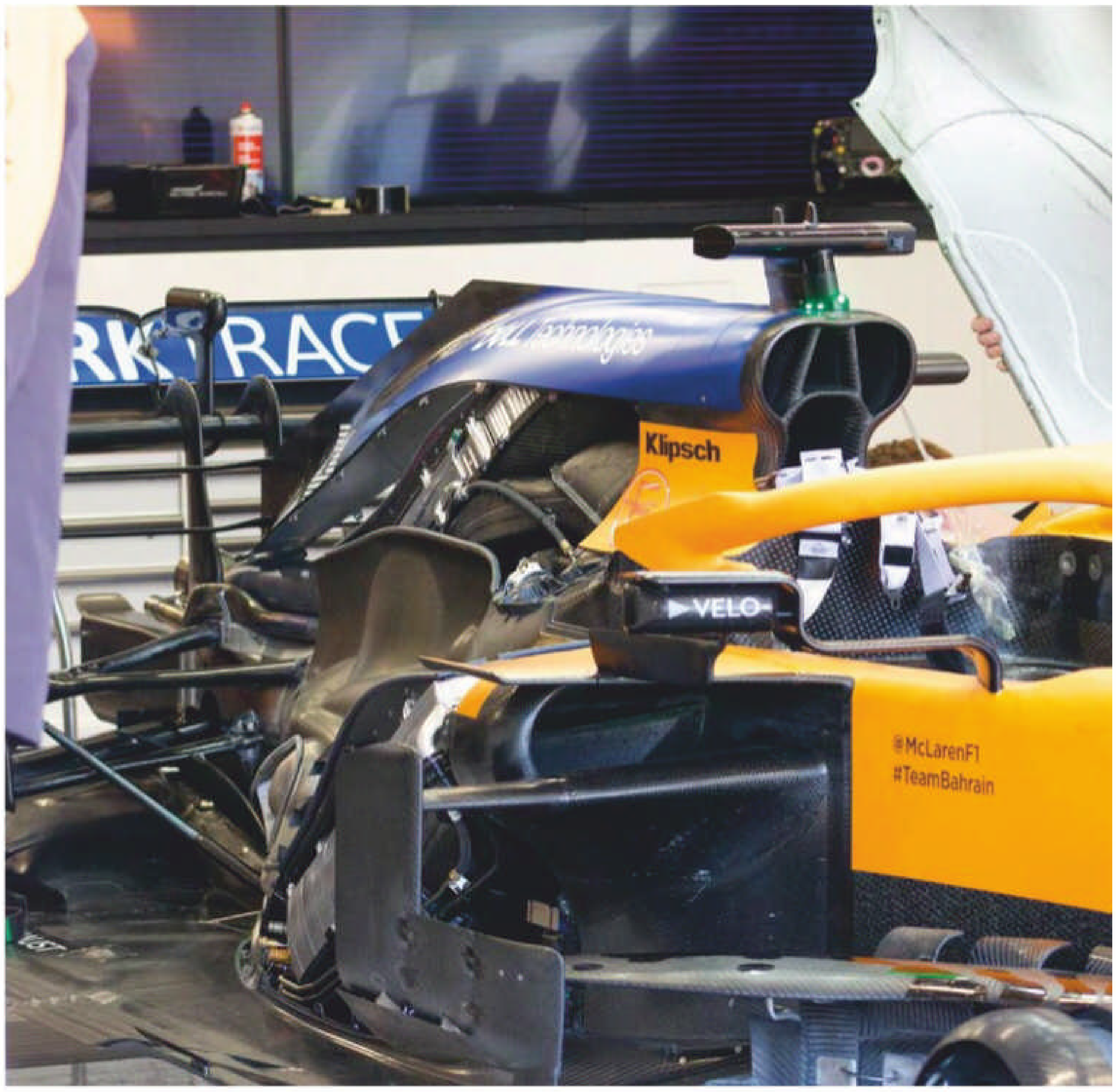
'Traditionally, drivers would be learning the circuit in free practice to have the best preparation, though from the technical side we needed to trade the driver learning for set-up understanding for the given event to maximise the performance where we had never driven before.

'I would say more than other years the collaboration has paid off, especially between myself and James [Key], which needed to be effective in terms of setting priorities and trying to cash in on the short and long-term understanding and development, which overall I would say is a point of strength at McLaren.'

2021: All change

Along with the cost cap for Formula 1 teams arriving in 2021, there is the planned chassis freeze and teams will also be limited on the number of upgrades they are allowed to make via a new token system. Additional limits to power unit upgrades, as well as number of exhaust systems drivers may use, will also come into force. The minimum weight of the cars will increase from 746kg to 749kg.

A new handicap system for aerodynamic testing will also be introduced, functioning as a sliding scale that reduces the amount of



Stewart Mitchell

The Renault Formula 1 engine installation in the McLaren MCL35

wind tunnel time as a function of position in the constructors' championship. This will follow a general cost-cutting reduction in aerodynamic testing and power unit bench testing restrictions, effective from 2020.

However, one of the biggest technical changes relates to floor design ahead of the rear tyres to reduce potential downforce gains. 'It's a shame it had to be done there, but there were good reasons for it,' admits Key.

'We are in the third year of these cars and they are getting quicker and quicker, to the point where resolution is lost for the drivers in some of the highest speed corners, so they go by instinct more than decision making. I think it is sensible to rein them in a little bit, and to ensure Pirelli can cope with even higher loads in the third year on the same spec of tyre.'

The changes have meant McLaren and other teams have had to do some bespoke aero development specifically for 2021 in areas that are challenging to characterise as the changes affect the floor, area around the rear tyres and diffuser.

'It has led to some unique development, and we have had to re-learn these quite critical and sensitive areas,' notes Key. 'In that respect, we couldn't carry over much, which would have been a much more natural progression. Of course, it's affected everyone the same way and there's good reason behind it. At the moment, we've got a fair bit of time to define the race one spec of the car from an aerodynamic point of view, and that's an ongoing process.'

Additionally, McLaren is switching power unit suppliers for 2021 from Renault to Mercedes. The Mercedes 2021 power unit installation sees a significant departure compared to the current Renault solution, as Key explains: 'A lot of the volumes are up front with the compressor being at the front of the engine, which in our case does help a bit with chassis packaging. The work we have done with our new colleagues at Mercedes has been really productive and very straightforward.'

At the time of writing, just after the final race of 2020, McLaren had already carried out significant rig testing at the Mercedes HPP facility, with Key noting: 'At the moment we're looking forward to getting going on the track with that Mercedes engine, and hope that it works out as well as our projections so far.'

Looking ahead

As far as on-track testing ahead of the 2021 season is concerned, it's the shortest amount in the history of Formula 1 since testing was sanctioned. As to how handicapped the team will be going into the first race of 2021, Key explains: 'It's been a case of trying to work in other ways to ensure reliability and understanding, and working closely with Mercedes on control strategies and the way systems work. These are the bits that could catch you out if you're not well prepared.

'We can go in and use those three days wisely to try and extract the most important information we need to hit the first race in good shape. There will be learning along the way, particularly for characterising cooling systems in hot conditions. Those are reference points we haven't got going with a new engine, but that's no different to any other year if you're changing engine.'

'We're looking forward to getting going on the track with that Mercedes engine, and hope that it works out as well as our projections so far'

James Key, technical director, McLaren Renault

As for predictions for 2021, McLaren's team principal, Andreas Seidl, is cautious about expecting too much from the team next year. At the last race of the 2020 season, he was candid: 'Despite the good result we have this weekend and, despite the great outcome for us in the championship side, with P3 I think we know exactly where we are. There's still a huge gap to the cars in front, especially the Mercedes car.'

McLaren should certainly be encouraged by the progress it has made with the MCL35, as well as its execution of race weekends and aggressive 2020 update strategy. Seidl concludes: 'I think the most important thing is to see that the team this year, under the leadership of [technical director] James Key, has produced a very competitive car. We have a clear plan of how we want to reduce the deficits [to Mercedes and Red Bull]. It will take time. But I'm confident that if we do the right things on the team side, we can close these gaps in some years.'

The switch from Renault to Mercedes for power unit supplier in 2021 will see some significant changes, due to the front-mounted compressor in the new engine package

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Asset management

What exactly does the future hold for F1 technologies?

By PETER WRIGHT

2020 has been a peculiar year. Apart from the immense Covid-19 test operation the FIA has successfully mounted to enable a World Championship that qualifies as such to take place, the only significant technical activities in F1, apart from DAS (dual-axis steering) have been to do with the regulations.

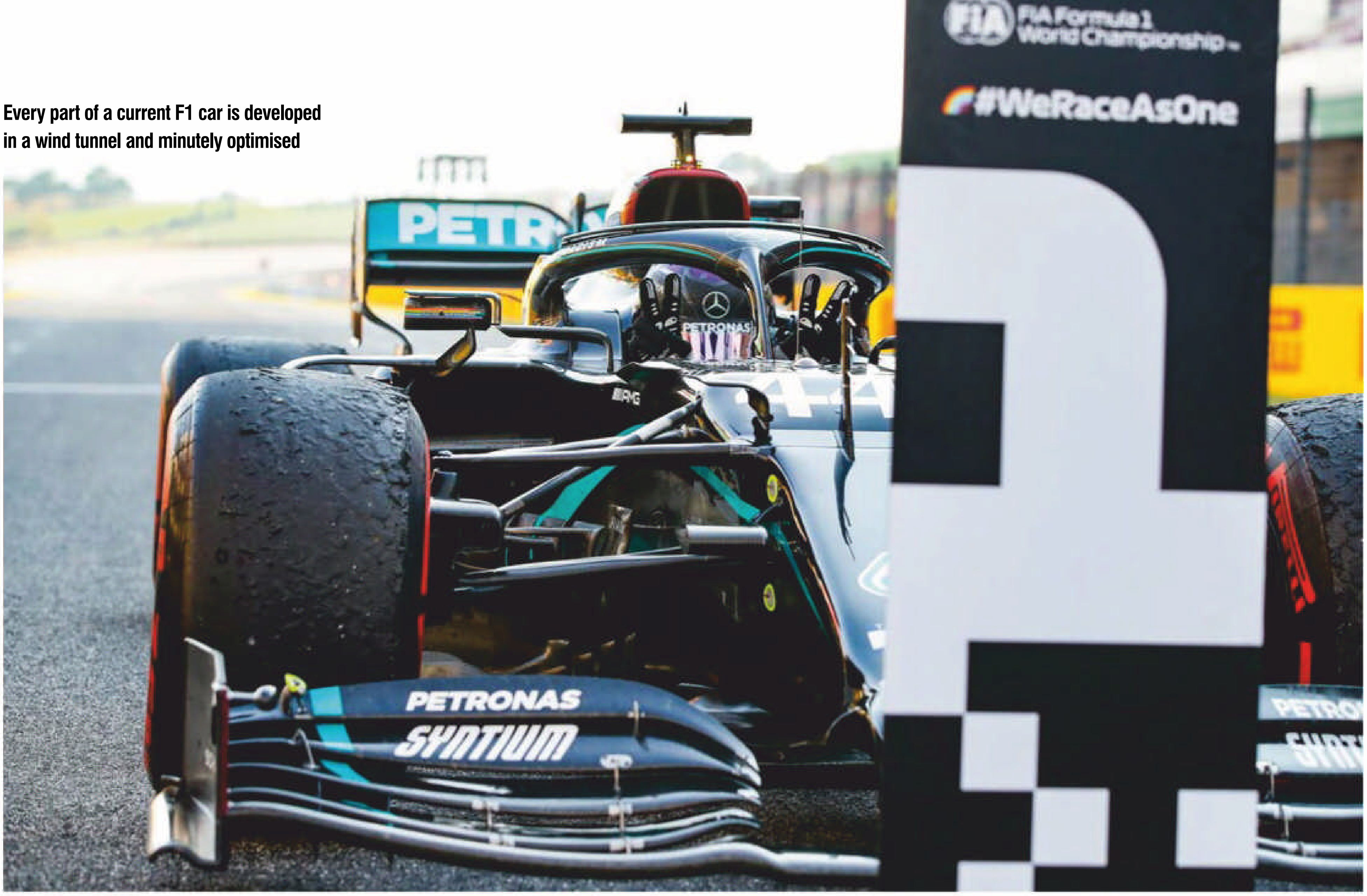
DAS, Mercedes' driver-operated front tyre heating system, was deemed too expensive for others to copy, and so summarily banned for 2021. Ferrari's 50-odd horsepower gain in 2019 was discovered by the FIA, but so clever was it that it couldn't be proven, allowing pundits to hypothesise and participate in 2020's favourite pastime of creating conspiracy theories. Racing Point's strategy of copying a Mercedes as closely as it could, but painting it pink, and rising up the finishing order opened up the possibilities of the hand-held photogrammetry and laser-scanning techniques now available.

With so much of the current cars either of fixed specification eg tyres, frozen, or of no longer significant technology that affects performance differentiation, there is diminishing technical interest for *Racecar* readers to pore over and enjoy.

Much of the current and next few years' F1 cars can be purchased from competitor constructors, and more and more of the composite and smaller parts are subcontracted out by teams, indicating again that they do not contain critical technologies.

There is still technical interest in the design, simulation, manufacturing, control

Every part of a current F1 car is developed in a wind tunnel and minutely optimised



With the cost cap applied, the team that can run their operation at the lowest cost should have the greatest surplus available to spend on R&D

Quite a change from the Peter Wright-designed Lotus 79, the first ground effect F1 car that dominated the 1978 season

and strategic software that so dominates the whole creative and racing activity of F1 but, for those outside the business, it is almost impossible to access or understand their important subtleties.

Science lesson

As the unusual 2020 F1 season concludes in the Middle East, and Mercedes continues to demonstrate the same dominance it has shown over the last seven seasons, the talk is all of cost cutting and how to make the formula both more sustainable and more entertaining, especially for the younger generations. The world appears to have finally 'got' climate change and to have accepted the science, but not what to do about it. The departure of Trump may finally release the brake on the politically and socially extreme measures that are necessary.

The established automobile industry has been shown the way towards electrification by newcomers – China and Tesla – and is now recognising that its ICE manufacturing assets will be stranded within a decade.

F1 is a series that relies heavily on the financial and technical support of the ICE automobile manufacturers and the oil industry. So what relevance will the series, as we now know it, have to these new industries? As has been acknowledged, there will be an awful lot of ICE vehicles around after the last piston engine has been manufactured (it has been predicted that for cars this could be as soon as 2028), and they will still require fossil fuels. The only way for the oil companies to prolong their business then is to provide sustainable fuels, but this too will mean stranded fossil fuel assets.

Footing the bill

F1 has finally imposed a cost cap on the manufacturing and operational sides of its participants' business. While the cost of making four or five F1 cars and racing two of them at 20-odd venues around the world is roughly the same for each team, the wealthy teams – Mercedes, Ferrari, Renault, and Red Bull – have traditionally received additional funds from their automobile and oil industry sponsors for the use of clever people and R&D. With a cost cap, and a reduced incentive to develop and promote ICE and fossil fuel powertrains, what will power the cars?

And, who will pay for them to be developed? The remaining sources of funding – tyres, energy drinks, fashion, computers, financial services, some faintly-disguised tobacco, alcohol, and B to B sponsorship – should continue, as hopefully will the income generated by putting on the show.

With the cost cap applied, the team that can run their operation at the lowest cost should have the greatest surplus available to spend on R&D. Apart from tyres and powertrains, which are excluded from the cost cap and which I will come on to later, what are the significant technologies to which these limited funds will be allocated?

Aerodynamics. The design and development of every part of an F1 car licked by the air stream is still the most cost-effective way of achieving performance. It is also still the great overtaking inhibitor that spoils the racing spectacle. The 2022 regulations are a serious attempt to reduce this problem, and the dropping of DRS, if and when it comes, will herald success in this quest.

Attempts to rein in the personnel and facilities costs of aerodynamic development are ongoing, and the banning of the use of wind tunnels is being discussed now that the validation of CFD is so good. More stranded assets? As aerodynamic development disappears inside powerful CPUs, what those developments entail will only be determinable by the most skilled and experienced observers of the end result.

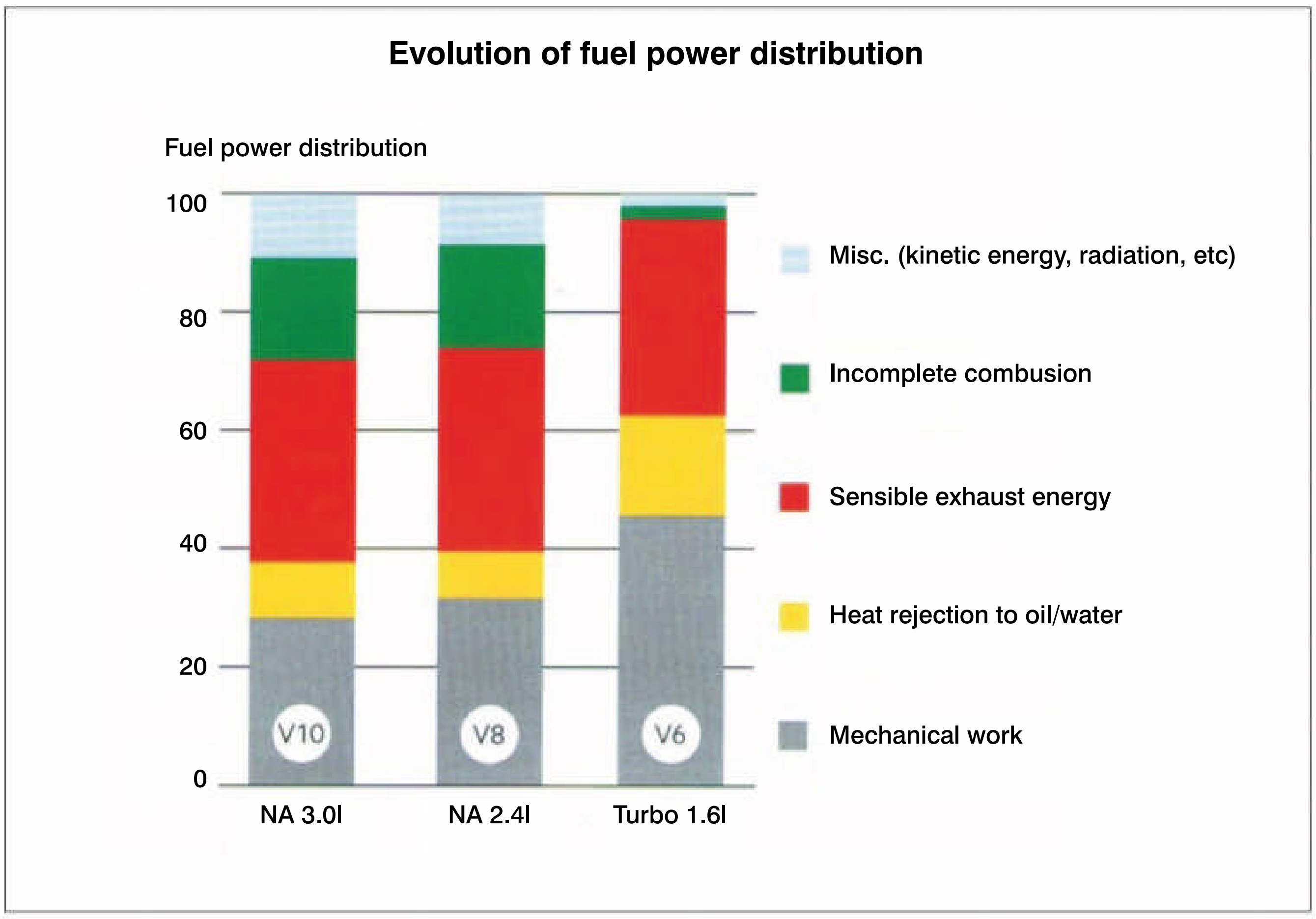
That aerodynamic development is so important, and the fastest way to better performance, is clearly illustrated by Racing Point's brilliant strategic decision to 'copy' the Mercedes by the lowest-cost methods it could devise. Only a slightly grey area in the regulations around the timing of a change in the rules covering the purchase of parts from other competitors caught the team out. Even after the saga died down, we still don't *really* know the why the Mercedes-designed rear brake ducts made such a difference!

Chassis. CFRP monocoque, suspension, steering, none of it is subject to major R&D, but it continues to evolve. Layout, wheelbase and weight distribution are all refined each year, as are the sophisticated suspension systems that control ride height and tyre management. Major changes to suspension layout are as much to do with aerodynamics as suspension kinematics.

The emergence of Mercedes' DAS took everyone, including the other teams, by surprise, as major innovations in suspension and steering are rare. We may not see another.

Brakes. The carbon-carbon brake is mature technology now, but it's cooling, along with its heat input to the wheel and tyre, and the cooling airflow's contribution to the overall aerodynamics continue to receive a great deal of attention.

Fuel flow meters are here to stay, which puts all the emphasis on the most efficient use of the fuel available



Even though this fuel power distribution graph was produced by Shell in 2016, it still shows the rate of progression

The F1 wheel must be the most sophisticated design in the world, and would blow the mind of whoever invented the wheel!

Tyres. These are about to undergo the first major change since Michelin introduced the belted radial to racing. F1 has used 13in diameter wheels for over 50 years, the deep sidewall profile providing significant contribution to the suspension requirements of the aerodynamically sensitive cars. The move to 18in diameter wheels, to bring F1 cars more in line with the styling of road cars, means not only the development of new tyres, but a change in suspension geometry and spring damper characteristics.

The cost of developing new tyres is outside the cost cap, but the collateral R&D needed for the cars is not. All for the sake of fashion…

Brakes and brake cooling will then have to be re-optimised of course. The cost of developing new tyres is outside the cost cap, but the collateral R&D needed for the cars is not. All for the sake of fashion…

Software. The level of electronics, data and control systems, is unlikely to change radically in the near future but the software, both on the car and available for analysis by the engineers, will undergo continuous development. The cost cap means fewer engineers will be available for this work, and so greater levels of AI will be developed to analyse and predict. F1 will follow the worldwide trend of software replacing people in all aspects of its business.

Safety. Romain Grosjean's accident in Bahrain will maintain the focus on safety, while showing so graphically just how safe being in a modern F1 car is today. The impact was akin to flying an aeroplane into a mountain: the fuselage breaks, the wings come off and there is a fire. Survival is pure chance. The only real issue is how to avoid the mountain in the first place.

Efficiency. In 2014, F1 introduced a new engine formula based on a fuel flow rate limit. As a result, the efficiency of a petrol ICE suitable for racing was raised from 30 something per cent to 50 something per cent, matched only by a diesel engine suitable for ships. The benefits for further R&D into improvements are now limited, and the auto industry that has traditionally funded this research has taken what is appropriate for road cars from it… just at the point when the future of ICE engines in cars is looking as if it is limited to about a decade. Why go on?

Romain Grosjean's fiery accident in Bahrain put safety at the forefront of everyone's minds. That the Frenchman survived with remarkably few injuries is testament to the success of the safety drive

The appropriate groups, plus the manufacturers involved in F1, are debating this question in relation to new powertrain regulations for 2025 or 2026. In the meantime, a second debate, with strong vested interests, is underway concerning the level and timing of a freeze appropriate to the current regulations (demanded for 2022 by Red Bull, if they are to take over the Honda powertrain) and whether, when the freeze does occur, there should be a Balance of Performance between the manufacturers. Mercedes and Renault are against, Ferrari is in favour, Honda (Red Bull) is not sure.

F1 will follow the worldwide trend of software replacing people in all aspects of its business

Hydrogen has been hailed as a future fuel, but extracting it uses valuable resource and creating and storing it in sufficient quantities poses significant safety challenges

In other words, it doesn't look as if much significant, or new, will occur in powertrain technologies before 2025 / '26. But what then?

The next chapter

With F1's agreed strategy of achieving sustainability, and its tactics of becoming a zero-carbon sport by 2030, the performance of the next powertrain will be central. Add to this the need to formulate regulations that continue to attract the automobile and energy industries, and avoid F1 becoming just an entertainment funded by wealthy individuals, and the challenge is clear.

It has already been declared that the next powertrain will employ hybrid ICEs and sustainable fuel. This makes sense in that the hybrid has proved to be the most efficient configuration for an automobile ICE, and sustainable fuels are going to be needed to fuel all the existing ICEs on the road that will still be around 10-15 years after the last one leaves the production line. Why the automobile industry should be interested in sinking R&D resources into a prime mover that has only a decade to go is not clear.

As the industry finally realises the future is electric, it can only be involved in Formula 1 to promote the brand. But as transport-as-a-service takes over and individual car ownership declines, it is not clear what role that brand will have.

The relative importance of the ICE component of the powertrain is also clear from the demand that the new hybrids cost 50 per cent of the existing ones. Improvements in efficiency are now on that part of the s-curve where ever smaller performance increases take longer and longer and cost more and more.

The purpose of the new regulations is therefore not to develop a better ICE, but to provide the only way of generating up to 1000bhp for as much as two hours, using energy that can be stored on the car without massively increasing weight and size. Which leaves the question of fuel.

Sustainable fuels

Sustainable means meeting our own needs without compromising the ability of future generations to meet theirs. In addition to natural resources, we also need social and economic resources. Youth movements led by the likes of Greta Thunberg have pointed out the importance of future generations' needs, and why they must be included when the ruling generation figures out what to do about the impending emergencies.

Sustainable fuels must be generated using 'unlimited' resources eg solar, wind, tidal, and possibly nuclear energy, or created from carbon and hydrogen available naturally in CO_2 and water respectively. Harvesting the necessary carbon and hydrogen from plant matter is not sustainable as it requires what are now limited land and fresh water resources. Biofuels are ultimately not sustainable, synthetic fuels are.

Audi backed Joule Unlimited to create e-fuels, and synthetic fuels seem to be the only way to go in the future

How tightly the new regulations are written, and how the sources of the hydrocarbons are policed, will determine whether fuel becomes a technical battleground for the energy companies in Formula 1, or whether there is collaboration for the greater benefit of society as a whole. The technologies for creating these fuels largely exists already, so whether Formula 1 can contribute significantly remains to be seen. Cost reduction is the main objective, and the existence of energy companies' fossil fuel assets is the major inhibitor.

The ICE automobile is pretty close to the peak of its performance / cost development s-curve after 135 years. F1 contributes little to society's needs for transport, at ever-increasing cost. That fact is firmly in the spotlight now, and the challenge for the small group of very clever people involved in renewing the F1 powertrain and fuel regulations – to both maintain its relevance *and* its value as entertainment – is certainly not to be underestimated.

Material development

Whatever the next set of regulations dictate, there will be continuous and valuable development of processes, simulations, design, manufacture and test technologies. New materials will be sought that provide better strength-to-weight, stiffness-to-weight and energy absorption-to-weight ratios, and computer-controlled additive manufacturing of parts that simply cannot be machined or cast will expand, with fibre-reinforced materials becoming an ever more important part of the process.

F1 contributes little to society's needs for transport, at ever-increasing cost. That fact is firmly in the spotlight now

Engineers will benefit by being involved in an activity that has been described by Ross Brawn as akin to taking part in a war effort, which thankfully has been avoided for several generations. The training this provides, learning the right attitude to getting things done and gaining self-belief, is one of the best schoolings for an engineer in any discipline that is available.

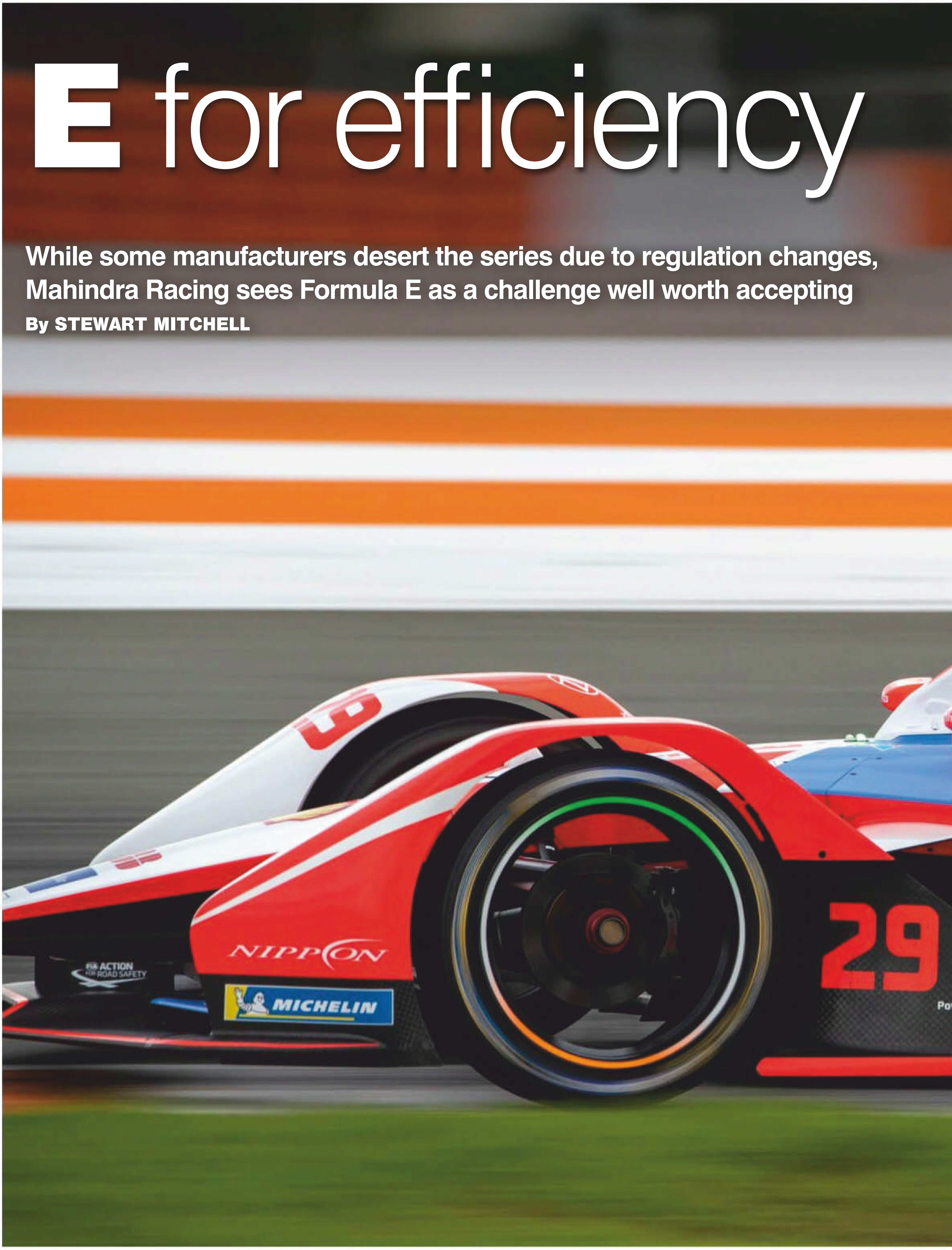
Perhaps the brightest light on the horizon is that, once development of F1 ICE-based powertrains tapers off, manufacturers may be prepared to publish technical papers on key F1 subjects. Honda has done exactly this for both its second era in F1,1986-1988, and third era, 2000-2008. The latter, a collection of an incredible 51 papers (available at www.hondarandd.jp/summary.php?sid=23&lang=en) is on a level with, for its time, Cameron Earl's report for the British Intelligence Objectives Sub-Committee on the developments of Grand Prix racing cars and land speed record cars in Germany between 1934 and 1939.

The days of rushing down to the paper shop to see what exciting innovations teams have come up with is long gone. But please Mercedes, tell us how you did it this time.

E for efficiency

While some manufacturers desert the series due to regulation changes, Mahindra Racing sees Formula E as a challenge well worth accepting

By STEWART MITCHELL



Formula E

Mahindra Racing, the longest standing Formula E team

What started as nothing more than a shared dream between Formula E founder, Alejandro Agag, and FIA president, Jean Todt, in 2011, the electric Formula E series has since developed into the fastest growing motorsport series on the planet.

Since its debut in the grounds of the Olympic Park in Beijing in 2014, Formula E has grown into a global series, gaining world championship status to become the ABB FIA Formula E World Championship ahead of the 2020 / '21 season.

With 12 teams and 24 drivers on the grid, the championship has become a destination for the world's OEM powerhouses. Although BMW and Audi have confirmed their withdrawal at the end of next season they will this year face Porsche, Nissan, Mercedes and DS Automobiles, Mahindra and NIO. The inclusion of OEMs in any series brings the need for greater resources, and therefore increased investment. Due to this, Formula E has evolved from off-the-shelf spec powertrain units to a level of applied engineering akin to Formula 1.

Regulation changes

For season seven, the FIA and Formula E have limited the running costs and closed technical avenues for exploitation, all in a bid to level the playing field. Formula E maintains the unchanged Gen2 chassis and the planned EVO update to the bodywork is being held back to manage costs. Racecar manufacturer, Spark Racing Technology, in partnership with Italian constructor, Dallara, will continue its supply of chassis to the grid.

The spec RESS (Rechargeable Energy Storage System) battery pack now supplied by McLaren Applied Technology also remains, and so too does the 54kWh output running at 880V. Additionally, the spec Battery Management System (BMS) inside the battery case, which manages the voltage, charge and temperature of every cell, as well as the charge / discharge cycles of the battery pack for maximum performance through a race and season also remains.

Motor speed has been capped for the first time at 100,000rpm, and the types of bearings used within the powertrain are also controlled for season seven.

Fewer data recording sensors can be put on the cars in 2021 when compared to previous seasons, with only data transmission allowed from specified sensors. VCU software is also being restricted to prevent changes and in an attempt to reduce in-season development costs. Going forwards, the VCU software must be homologated seven days before each race and the software spec for the entire season declared before the championship starts.

Formula E

Mahindra Racing team principal / CEO, Dilbagh Gill

On the hardware side, the power modules such as the VCU, steering wheel, DCAC converter, power box and brake-by-wire units are limited to two per car per season, and only three carbon rear casings, and radiators, and six driveshaft sets to last the full season.

As with previous seasons, the teams cannot change or develop any part of the chassis outside the regulated powertrain envelope. The freedom for hardware development is therefore limited to motor, inverter, DCAC, VCU, final drive, rear suspension (excluding rear uprights), driveshafts, powertrain cooling package, wiring loom and the rear subframe (between the monocoque and rear impact structure). Numerous technical regulations control what manufacturers can do with each of these elements, but the entire powertrain package must weigh in at under 125kg.

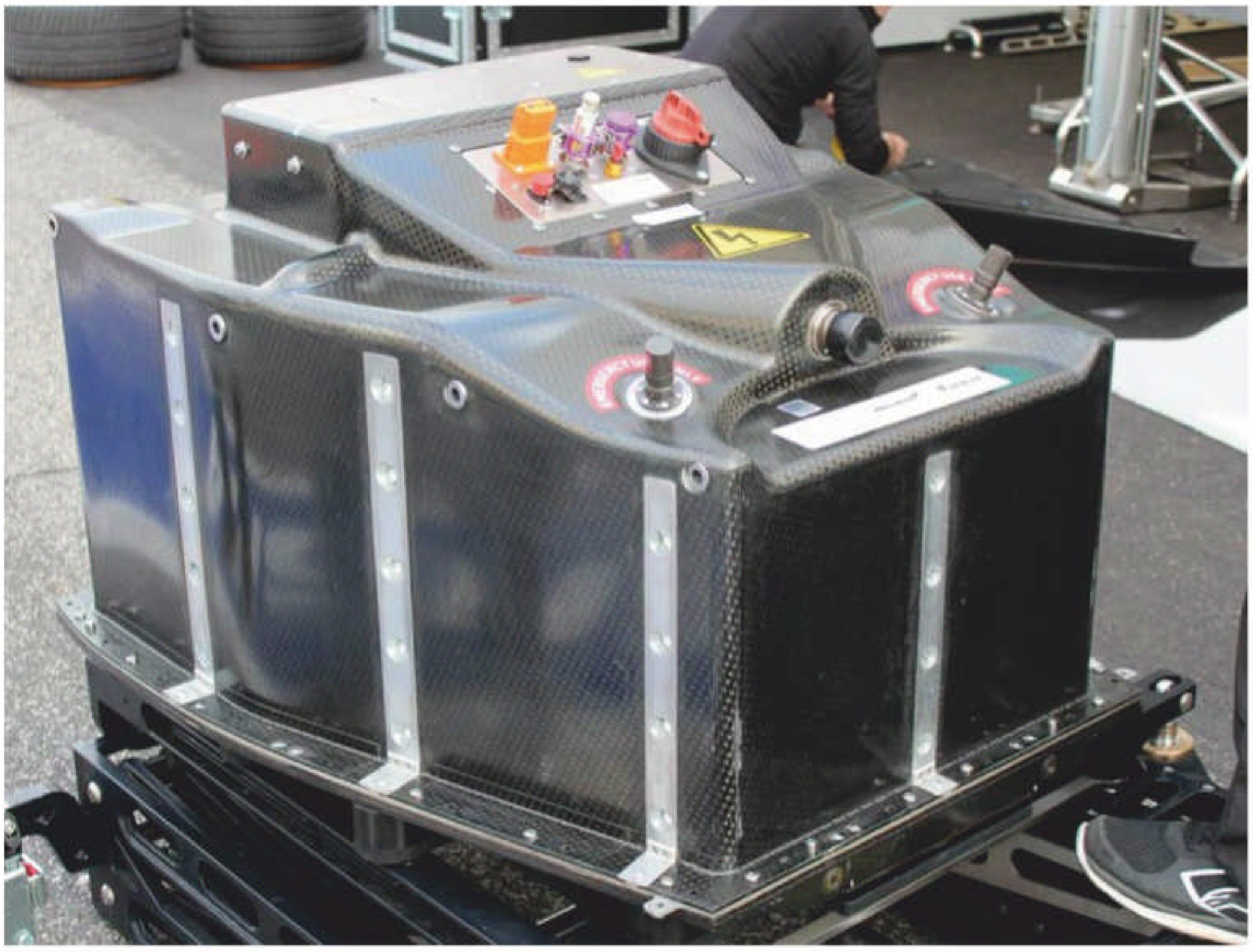
These changes have had a huge effect on the technical challenge of Formula E, and therefore the technological advancement potential the sport has for OEMs using it as a test bench for future road car powertrains. Despite Audi and BMW both announcing they will leave the championship at the end of season seven, this still leaves a strong field of manufacturer and privateer teams on the grid, the longest standing of which is Mahindra Racing that, for season seven, produced the M7Electro.

Design challenge

Team principal and CEO of Mahindra Racing team, Dilbagh Gill, describes the challenge of Formula E as one of powertrain design. As Formula E specifies the power output of the car, the governing body is able to measure the input and output of the battery. Controlling the output of that power is down to the teams, though, to lose as little of the 54kWh the cars start the race with through electrical losses and mechanical friction. The higher the efficiency of the powertrain, the more energy they have to deploy to the circuit for the 45 minute + one lap races.

In all cases in contemporary Formula E, the cars run a permanent magnet synchronous

Teams cannot change or develop any part of the chassis outside the regulated powertrain envelope



Stewart Mitchell

The 54kWh spec McLaren battery, which powers all Formula E cars on the grid

MGU (Motor Generator Unit) that works both to drive the car forward and recover energy under braking. The output of the motor is capped at 250kW, equivalent to 335bhp. Many of the current Formula E electric motors weight around 20kg and their characteristics are such that they make full torque from zero rpm up to a maximum of around 30,000rpm. Such motors drive a single drop gear to the final drive.

As the MGU requires an AC power source created from the DC battery, DC to AC conversion is necessary, and Formula E level cars employ inverter / rectifier units to make the conversion between DC and AC, both in deployment and in regeneration. Within the inverter, silicon carbide MOSFET switches are used to control the switching of currents.

Formula E

The Mahindra Racing M7Electro on track for the first time in Valencia during pre-season testing

All-new powertrain

According to Gill, the most important feature of the M7Electro from Mahindra Racing is the all-new powertrain, coming from the team's powertrain partner, ZF. 'Along with ZF, we spent a long time changing every part of the powertrain, so this is a brand new car coming for season seven,' says Gill. 'The development we've seen on the dyno, and on the track while testing, is pretty exciting, and the M7Electro is a big step forward for us.

'Our partners, ZF and Shell, have done an excellent job producing something that is incredibly efficient.'

ZF has been working in Formula E in various guises throughout the first two generations of the series, seeing it as an appropriate place for MGU and gearbox technology development. A few years ago, the company formed a completely new development team within ZF Motorsport, specifically dedicated to e-race development. This team is investigating all types of e-machine technologies, inverter technologies and appropriate transmission design. This includes things like silicon carbide switching technology for the inverter, all the way through to grain structure and surface finishes of the transmission drives.

The ZF team is also tasked with understanding and developing driveability within all of these e-powertrain components. This very delicate equation for optimum efficiency means it is well positioned to accommodate Formula E's powertrain targets, and to look for areas where

'The development we've seen on the dyno, and on the track while testing, is pretty exciting, and the M7Electro is a big step forward for us'

Dilbagh Gill, team principal and CEO of Mahindra Racing

Mahindra Racing

Season seven Formula E regulations maintain the Gen2 chassis in a bid to save costs

efficiency can be improved, which isn't easy when the motors and inverters have reached now 99 per cent efficiency.

'Where we're making huge strides right now is with the gearbox and the differential, which left some things to be desired with the efficiency the motors operate in,' says Gill. 'We started with ZF a year before the powertrain got in the car, and were able to evaluate the concept pretty strongly working throughout season six.

'As far as the development of the powertrain is concerned, there is a significant difference between the season six and season seven version in terms of power delivery and management. It's also not in the same position it was in the season six car.

'The concept in terms of speed and rpm vs torque is considerably different as well. There is a lot of work that has gone on in the background in terms of simulations, and understanding what we were doing in season six, and taking that into development for season seven.'

Sascha Ricanek, managing director at ZF Race Engineering adds: 'As the chassis parts remain the same for all cars, we can only attack on the powertrain side and here there are two dimensions – efficiently and weight – that we are working on.

'The collaboration with Mahindra, and the feedback we get from the drivers, is extremely important to us. This partnership works so well that last season we had the opportunity to improve these two factors tremendously. We hope to see this in the feedback going into season seven as well, so we can further improve the efficiency and get the weight down for the future, which will help us in overall performance.

'We started developing this Formula E powertrain even before the ink was dry on the contract since the time pressure is tremendous, and the Formula E development curve makes huge steps year on year.'

Unsurprisingly, ZF has a team of people working on the Formula E powertrain project, not only directly from the ZF motorsports side, but also from its e-mobility division, where the knowledge gained and investigations undertaken go more into road car and other mobility platforms.

Learning curve

BMW-i Andretti is the one team believed to be using a longitudinal set up on its powertrain cluster. As to whether this was this something ZF and Mahindra looked at for the design for the M7Electro, Ricanek would not confirm, but did say, 'We are trying out a lot of things in the background since Formula E is an extremely steep learning curve for all of us. At the end of the day, you need to see which kind of components you have for weight and which kind for capability in terms of bringing the utmost performance out of it, so of course we are always looking in all directions to improve ourselves, and that's why we came up with this totally new powertrain concept as it is now. We hope it's the one which is right to win.'

As there's a direct link between the speed of the motor and its inertia, this has to be carefully considered when it comes to the design of the gearbox. Ricanek explains that optimising this is a case of managing settings in the power curve, taking into consideration how the drivers are using the power settings and their feedback regarding driveability.

'We have worked tremendously hard on settings, and still it's a learning curve for us because every race is totally different. You cannot predict who will perform well under which conditions, and so it's very tough to find the one and only power setting and combine that with the output ratio we are using. Hence there is not one setting we are using every time. We are trying to optimise the software as much as we are allowed to within the regulations.

'We always have to consider on the hardware side how much weight we can afford, both on the gears and on the whole design of the box, as this is something that drives overall efficiency'

Sascha Ricanek, managing director at ZF Race Engineering

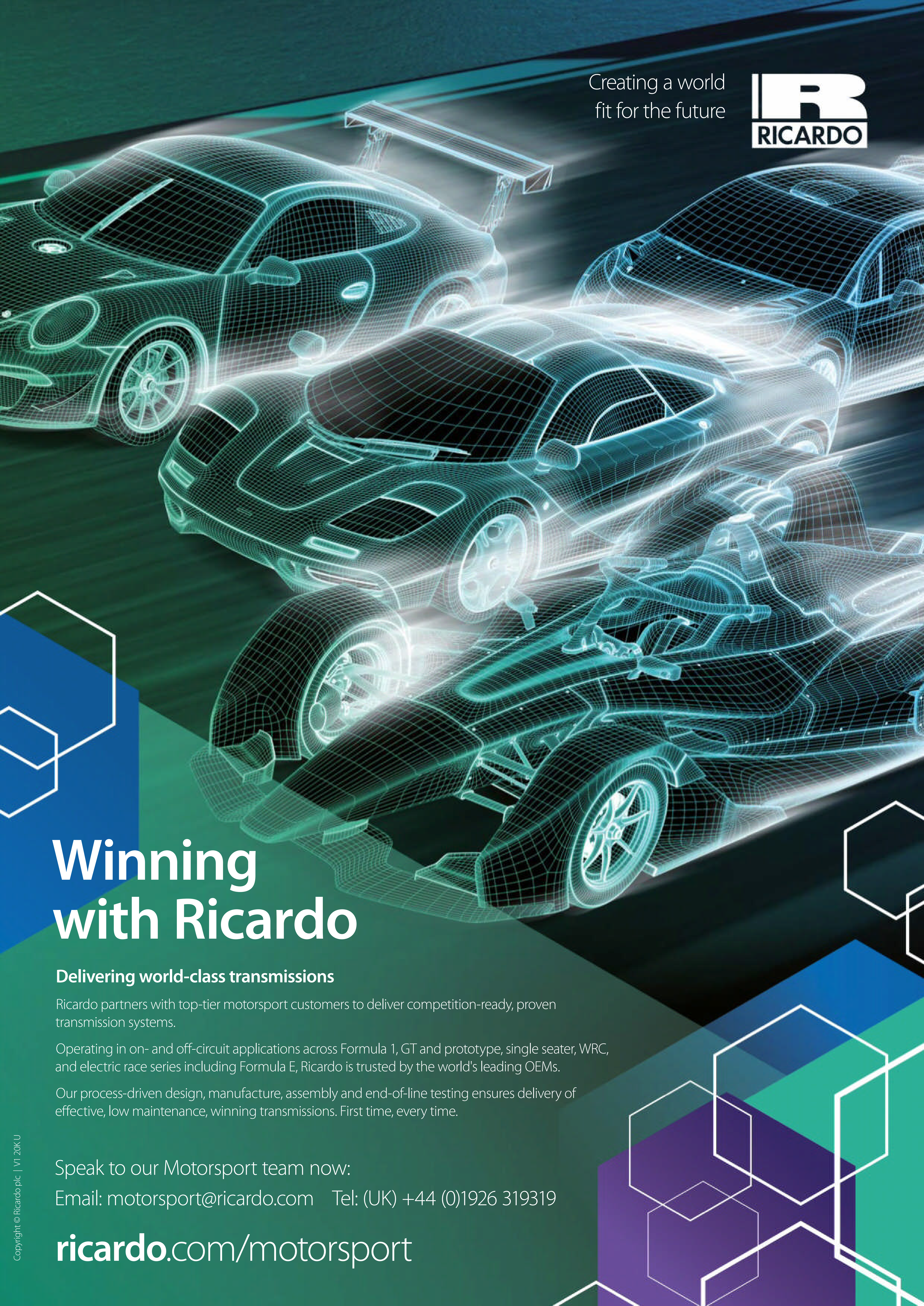
The development process, and the structure of the gears themselves, are very different for an electric powertrain because of the entirely different power curve and way torque is delivered. However, weight remains a fundamental concept. 'We always have to consider on the hardware side how much weight we can afford, both on the gears and on the whole design of the box, as this is something that drives overall efficiency,' confirms Ricanek.

Software

With just a single drop in speed from the motor to final drive, the motor design must be able to produce power efficiently over a huge range of motor speeds. To ensure the torque transfer is effective across the range as well, the motor and gearbox design are done in parallel. Although the mechanical structure of the motor determines some of its characteristics, much of its behaviour can be dialled in through software.

Mahindra Racing

Mahindra Racing moved to a new factory ahead of season seven and agreed to the Gen3 regulations, cementing its commitment to the series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Formula E

Mahindra Racing's performance at pre-season testing showed great potential for the team

'We find the right setting as far as motor design, and then change the interaction of the entire system through software,' explains Ricanek. 'This is fundamental practice for getting the whole powertrain to maximise efficiency between the interaction of all the parts.

How Mahindra tackles software updates over a race weekend, and how this affects the way the new powertrain is operated through the season, is a key element of the competition, and one Ricanek believes gives ZF an advantage over the competition: 'Of course, we are trying to balance out whatever is allowed by the regulations. On the hardware side, we are quite limited for changes, so our effort is mainly on the software side. We found a strategy we can adapt from race to race, and from circuit to circuit.'

Lubrication

For two years, Shell scientists in Hamburg and Bangalore have been working alongside Mahindra's R&D department to develop fluids for Mahindra Racing's powertrain. 'The extreme conditions at Formula E races provide a perfect experimental platform for new electric drivetrain technology, especially transmissions,' says Ricanek. 'Working closely with Mahindra Racing and ZF, Shell has developed a dedicated e-transmission fluid for the car, which enhances the efficiency of the transition and, in turn, improves the car's performance on the racetrack.'

According to Ricanek, Shell's lubrication has heavily influenced development of the gearbox, and provided a lubrication regime that has enabled the ZF team to find efficiency gains throughout.

'It's key for us to understand what kind of liquids are available, and how the fluid contributes in terms of our performance,' Ricanek notes. 'We cannot develop a system domain and then the fluid comes in, we need it to go hand in hand, which we did.

'The time constraints we faced, though, and collaboration under Covid situations was tough, but we managed it and Shell provided us with an excellent fluid, which hopefully will give us the performance we need now.'

Close racing

Formula E rule has been designed to promote close racing. The qualifying format means front runners in the championship qualify a bit further down the field, which promotes wheel-to-wheel action. The cars are forgiving on the tight, bumpy street circuits the series races on, which entices mistakes from drivers trying to navigate them on the limit. Furthermore, a low dependency on aerodynamics means cars can follow closely, which all makes for good racing.

For series seven onwards, the tracks have been modified so there are fewer chicanes. As to whether this informed any of the design process for the powertrain, Ricanek says, 'Yes and no. On the hardware side, not too much, but on the software side, of course, we trying to improve and to get the utmost ability to adapt to the different circuits and the layouts, which is still a learning process.

'As every year we have a new powertrain, we start from zero and have to learn how to optimise the settings, but with good collaboration and feedback from the drivers, we can change and adapt our development in the background between races, and even between sessions.

'This collaboration was tremendously good in the last year, and in the development of the season seven powertrain, so we think we have achieved quite a good result, but still we will see where we are in the first race in Chile. Let's cross fingers that the result on track there is as we have seen on the test bench.'

'It's key for us to understand what kind of liquids are available, and how the fluid contributes in terms of our performance'

Sascha Ricanek, managing director at ZF Race Engineering


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Balance of Performance now governs a wealth of motor racing formulae, reducing the need for development as the regulators will take care of any deficiencies for you

Making BoP changes

Not guess work, but an engineering problem that follows the scientific method. Here's how

By SCOTT RAYMOND

In the last article on Balance of Performance (BoP) in *RE* V30N11 we explored two key concepts: the physics of vehicle performance, and the options available for making changes to the balance of performance.

In this article we will examine the actual process of making BoP changes. It is important to keep in mind that the challenge of balancing disparate vehicles is an engineering physics problem, and the potential solutions can usually only be drawn from the list of available parameters to change.

But how can we know if a change in performance is required, or which vehicle parameter to modify to affect this change?

Despite what many pundits may believe, the process of making BoP changes is not black magic, nor based on a random number generator, it is truly an engineering problem that follows the scientific method. It begins by asking a question and ends by forming a conclusion.

With the BoP process, we must ask the following question prior to each event: 'Will the expected performance of all vehicles competing at the upcoming event be balanced?' The conclusion formed following each event is either; 'yes, the performance of all vehicles competing at the event was balanced,' or 'no, the performance of all vehicles competing at the event was not balanced.' Sometimes, it might even be 'the expected performance of all vehicles was not demonstrated, so I have no idea if the vehicles were balanced or not!'

Between these initial and final steps, the remaining phases of the scientific method are followed, which include conducting research, forming a hypothesis, performing an experiment, collecting data and analysing and reviewing that data with the objective of forming a conclusion. Once the conclusion is drawn, the final step of the process involves generating a report to communicate the findings of data analyses and provide factual evidence supporting the conclusion.

I want you to think about the experiment phase of the Balance of Performance process as a race event. With each BoP change made (and those not made) prior to a race, an evaluation of the success or failure of the change is formulated based on the performance of the vehicles in the practice, qualifying and race sessions. Put it into your mind now that the BoP process can be simplified down to first asking a question, then racing, and finally forming a conclusion.

Despite what many pundits may believe, the process of making BoP changes is not black magic, nor based on a random number generator

As with all implementations of the scientific method, the Balance of Performance process is a continual cycle. With each passing event, vehicle test or new vehicle appraisal, the cycle repeats itself, with the knowledge gained from the past contributing to the assessment of the next event. The BoP process is, or at least should be, in a constant state of improvement where more useful, accurate and comprehensive models and methods are developed with each iteration of the cycle.

Now let us look at each step in the process in detail as it relates to the scientific method.

Step 1: The question

'Will the expected performance of all vehicles competing at the upcoming event be balanced?'

First, take note of the word *expected*. We can go down several rabbit holes trying to explain what we mean by that. I use this term to place an emphasis on the fact that we must always deal with variables when conducting the BoP process. Typically, these variables are beyond your control, such as weather conditions, a car crashing, sustained damage inhibiting a vehicle's performance or the recruitment of a driver into a team's line up for whom you have no previous data.

I also want to emphasise expected as a reminder that performance demonstrated by a manufacturer / team / car / driver is the sum total of what they *choose* to demonstrate. Yes, I am referring to sandbagging and performance management, a topic we have discussed previously at length. When the demonstrated performance does not match the expected performance, either your expectations are wrong, or the only conclusion that can be made is inconclusive.

Next, let's talk about the phrase *all vehicles*. The objective is that every single car is competitive but, in truth, many cars simply do not have a chance. Whether this is related to driver talent, engineering skill or team execution, these factors can be lumped in with those beyond your control. So, all vehicles should better be clarified as 'the best representatives of each manufacturer vehicle model'. Because we are in a situation where cars representing various manufacturer brands are competing against each other, it is better to think about each brand as a unit that is measured against the other brands competing.

Finally, *upcoming event*. During a racing season, the next event on the schedule is obviously the upcoming event. However, this becomes less clear cut when we talk about the first race event for a group of vehicles, such as the 2016 IMSA Daytona 24h, which saw the introduction of all-new, never before raced GTE models in the GTLM class, and new-to-series GT3 models in the GTD class. The BoP process is quite different here when dealing with a group of unknown vehicles, so it is important to distinguish between racing unknown quantities vs racing known quantities.

The last note on upcoming event is that the event takes place in the future, and so the BoP process is very much about predicting the future!

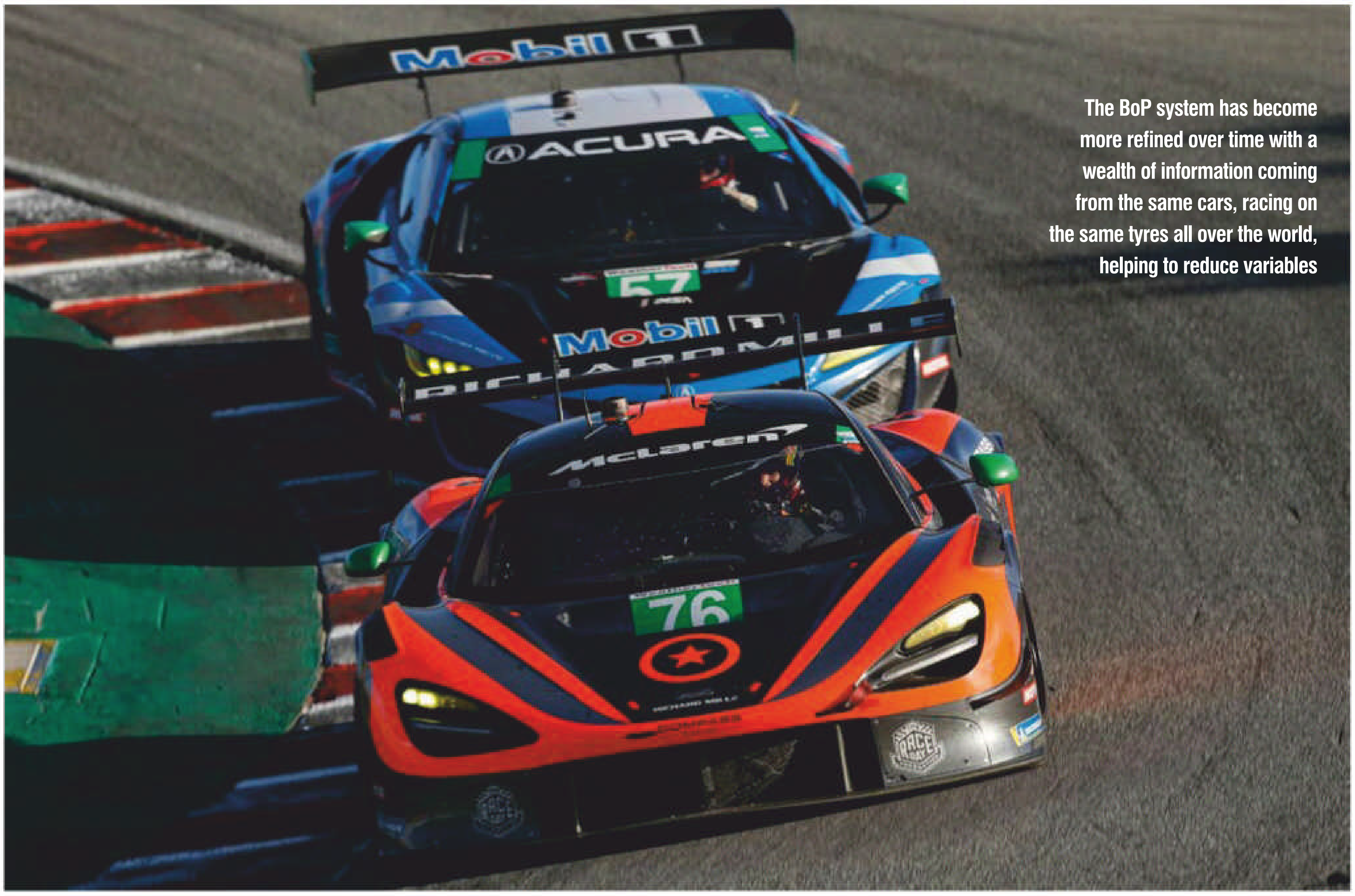
Step 2: Research

The research phase of the BoP process involves collecting as much information and knowledge as necessary to form the best possible prediction (hypothesis) of the expected future performance of each vehicle type competing at the upcoming event.

Here, different methods are used when dealing with unknown quantities vs known quantities. When all vehicles are unknown, or when a new vehicle model shows up, the research is much more involved and often requires a series of separate experiments to quantify certain parameters of each vehicle's performance envelope. One must learn before making a prediction.

In such a case, the only option for predicting vehicle performance is via simulation, but simulation is a dangerous tool in the wrong hands. It is easy to run simulations and generate all kinds of lap times and pretty graphs, but if the vehicle models are flawed, or inaccurate, all the pretty pictures in the world won't save your ass. Therefore, it is necessary to obtain valid data quantifying the performance characteristics of various vehicle systems

Balance of Performance (BoP) was originally introduced to manage the Maserati MC12, bringing an end to the dominance of the Ferrari 550 Maranello (bottom)



The BoP system has become more refined over time with a wealth of information coming from the same cars, racing on the same tyres all over the world, helping to reduce variables

If the vehicle models are flawed, or inaccurate, all the pretty pictures in the world won't save your ass

such as masses and inertias, powertrain, aerodynamics, suspension and tyres. Recall we are discussing a physics problem, so the closer the simulation vehicle model is to the physical vehicle, the closer the simulated physics will match the real-world physics.

When working with vehicles that have already raced, you should be armed with historical data, and hopefully you have also correlated your vehicle simulations to that data. You should have an established database of vehicle performance parameters, so predicting future vehicle performance revolves more around applying current knowledge to the circuit layout for the upcoming event. As with the process of dealing with unknowns, simulation is again a key step in predicting future performance. However, with refined, accurate vehicle models, the simulation results should more closely match reality.

Another part of the process involves quantifying the characteristics of historical circuits and comparing these to the upcoming circuit to look for similarities. For example, a vehicle that performs well at low-drag circuits should perform equally well if the upcoming circuit has several long straights.

The results of the research phase should put you in a position to understand if any vehicles will exhibit a performance deficiency or advantage at the upcoming event. Furthermore, you should understand *why* those deficiencies or advantages exist. If the results of your research indicate the vehicles will demonstrate similar performance, no changes are required for the upcoming event.

Returning to the concept of the physics problem, you should now have a good understanding of the longitudinal, lateral and combined acceleration characteristics of each vehicle, and how those characteristics will influence performance at the upcoming circuit.

Stage 3: Hypothesis

Now it is time to apply the results of your research. In cases where the research indicates the vehicles are expected to demonstrate similar performance at the upcoming event, the hypothesis is simply to do nothing, and the cars should be balanced.

However, when the research indicates an expected imbalance, you must determine what vehicle parameters to change to neutralise it. Recall the list of parameters discussed in the previous article, which include mass, total power output, minimum ride height, aerodynamic elements, fuel capacity and tyres. How do these parameters influence the expected longitudinal, lateral and combined acceleration performance of each vehicle? To answer this, we must consider the impact of mass, power, minimum ride height and aerodynamics on each of the acceleration components. Because minimum ride height has an influence on the aerodynamic performance of a vehicle, we will lump ride height changes together for the purposes of effecting aerodynamics into the aerodynamics category. The influence of ride height with respect to centre of gravity height will be considered separately.

Positive longitudinal acceleration, or throttle application, needs to be separated into low- and high-speed accelerations. At lower speeds, racing vehicles are typically exiting slower corners and accelerating in a low gear from a relatively low rpm level. Under these conditions, longitudinal acceleration is maximum and vehicle mass and engine torque have the greatest influence upon it. At higher speeds, racing vehicles are typically travelling along straights in top gear and at a high rpm. Here, longitudinal acceleration is minimum and aerodynamic drag and engine power have the greatest influence upon it.

Negative longitudinal acceleration, or braking, typically starts as a high-speed event and transitions to a low-speed event. During the initial high-speed phase, aerodynamics plays the biggest role in braking performance. As speed reduces, mass and ride height play a bigger role. In this case, the impact of ride height on centre of gravity height can increase or decrease the longitudinal load transfer from the rear axle to the front axle.

Lateral acceleration also needs to be considered in terms of low-speed and medium / high-speed components. The lateral acceleration at lower speeds comes from travelling through a low-speed corner, where mass and ride height (due to the influence on centre of gravity height and lateral load transfer) contribute the most to the maximum lateral acceleration achievable. Most vehicles achieve the highest lateral acceleration in medium / high-speed corners with larger corner radii. In these corners, the aerodynamic performance of a vehicle has the greatest influence by far.

Combined acceleration occurs when the vehicle is either braking and cornering or accelerating and cornering. As such, all parameters can have influence. When an issue with combined acceleration occurs, it is important to look at how changes to BoP parameters influence the longitudinal and lateral accelerations and choose the best compromise.

Deciding which parameters to change is anexercise in compromise. Because many influence multiple accelerations, the objective is selecting the best compromise that least impacts performance in other areas.

Stage 4: Experiment

The experiment begins with publishing an updated BoP table for the upcoming event. It is in this phase of the BoP process that the rubber meets the road, literally, and the outcome of the experiment is in the hands of the manufacturers, teams, drivers and weather.

It is critical to ensure any data collection methods are working properly, so be proactive during the practice sessions and verify the functionality of data systems. It is a good idea to have back-up plans too, just in case a failure occurs. For example, if the racing vehicles are running a series data logger, have an agreement with the manufacturer to provide data from their logger in the event of a series logger failure.

It is equally important to watch the sessions and race as they unfold, paying close attention to the on-track action. Take a lot of notes during the race to capture any extraneous information that can influence the performance of a vehicle, such as tyre strategy, driver line up, set-up changes during pit stops, crash damage, repairs and fuel strategy.

The only other thing you can really do is hope it doesn't rain. Or snow, if you are at the Nürburgring!

Stage 5: Data collection

Without proper data, any conclusions from the experiment are simply opinions. Manufacturers will eat you alive if conclusions are not supported by data, and you will lose respect.

The most general data source is lap timing. Timing data resolution is improved greatly with multiple circuit segments that divide the course into smaller chunks, but ensure none of the timing lines are in braking zones as that screws with everything. Great timing data will include information about who is driving each car, multiple segment times, multiple speed traps, pit stop indications and time spent in pit lane.

A significant improvement in understanding vehicle performance comes with the collection of logged vehicle data. In some cases, teams may be required to share data from their logger with a racing series, but it is more secure to have a dedicated series logger with some specific series-only sensors. At a minimum, a series logger

Because many [parameters] influence multiple accelerations, the objective is selecting the best compromise that does not significantly impact performance in other areas

Despite the first BoP system, Maserati's MC12 was able to perform well on all types of circuit, and in all weathers, enabling it to take multiple GT titles

The SRO holds an extended pre-season test at the versatile Paul Ricard circuit in France in order to finalise its analysis of the various types of car and layouts

must capture GPS coordinates and speed, lateral and longitudinal accelerations, yaw rate, driver inputs for throttle, brakes and steering, fuel consumption, lambda, gear position and powertrain channels. The list of required powertrain channels can be quite long, and is highly dependent on the powertrain architecture. Ideally, they should be sufficient to ensure the powertrain is always operated within the regulations.

Additional sensors such as dynamic ride heights, wheel loads and pitot pressure are exceptionally useful when working with vehicles that rely on aerodynamics.

It is possible to get more granular by collecting data that is specific to certain vehicle systems. For example, to better understand pit stop times, it is important to monitor refuelling times and fuel flow rates. Equally important is the collection of tyre change data to understand when tyres were changed and when different compounds were used.

Another useful data source is on-board video footage, which helps to show what actually occurred at a specific time and location in the race.

The whole point of data collection is to paint the clearest picture possible about the vehicle performance.

Step 6: Analysis

With all the data collected, it is time to analyse it, recognising that both the analysis and research phases are somewhat interchangeable. When analysing the data from a current event, you are basically doing the research for the upcoming event.

The results of the data analysis should allow you to form a conclusion about the performance balance for all the vehicles. Your choices here are yes, no or inconclusive. When the answer is yes, that is wonderful. When the answer is no, at least you know something needs to change. But when the answer is inconclusive, you receive zero reinforcement, either positive or negative, and that is very frustrating for BoP engineers.

Stage 7: Report

The final phase of the process is generating a report that summarises the analyses and provides concrete evidence for your conclusions. It should be clear, concise and indicate if any component was inconclusive.

Several racing series share their BoP reports with the manufacturers, which is an excellent idea, as it builds confidence and respect when a racing series is transparent in this way.

Testing for changes

There are two general types of changes that can be made to BoP tables: proactive and reactive. The former may be made before a racing season begins, after simulation or during a season, in anticipation of some potential imbalance in performance. The latter are made after a performance imbalance is observed.

Most racing series and sanctioning bodies that employ a BoP process conduct on-track BoP testing before a season begins. The best is done using a skilled, professional control driver who pilots all cars under similar conditions at a circuit that is representative of the types encountered during the racing season. Using a control driver eliminates the two main variables that hamper BoP testing; driver inconsistency and sandbagging. As a control driver has no incentive to manage performance, assuming he or she has suitably flogged each vehicle, you should come away with a good amount of useful data and detailed notes about the driver's experience in each car.

Personally, I don't feel on-track BoP testing alone is sufficient to gain a complete understanding of a vehicle, and believe it important to incorporate further testing methods that complement these tests and make it easier to conduct vehicle dynamics simulations.

The whole point of data collection is to paint the clearest picture possible about the vehicle performance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For example, engine dyno testing should be completed for all vehicles to obtain maximum engine power and torque figures, along with power and torque curves. When conducting engine testing, it is important to test multiple engine restrictors or boost control curves to understand the sensitivity of the engine output to such changes. With these tests in the bag, you will be equipped to make BoP changes to engine parameters in the future as you will know their effects on performance.

In addition, it is essential to understand the impact of ignition angles / engine timing and fuel mixture. Then, when you are reviewing vehicle data in the future, you can use date to explain how changes in those parameters influence the observed performance of each vehicle.

Aerodynamic testing is critical when vehicle performance is highly dependent on aerodynamic performance. Tests should be done to understand wing angle sensitivities, the effects of dive plane or wicker options and the influence of ride height changes on aerodynamic performance.

Where resources are available, it is also nice to scan each vehicle so solid models can be produced for CFD simulations, which are considerably cheaper than hours spent in a wind tunnel.

A significant amount of labour-intensive work is required following BoP testing, but what you hope to gain are things like acceleration profiles, braking and cornering capacities and traction control differences, among other things. While this may be difficult, it will make your job less complicated in the future.

Finally, with a solid understanding of on-track performance, engine and aerodynamic performance, you can work with vehicle dynamics simulations to try and virtually balance the cars. Remember to factor in any drivetrain losses, because again they can be different between cars. It is possible to estimate these losses if you know the drag characteristics of a vehicle.

In-season changes

Proactive changes made between events during a racing season are generally due to a change in circuit characteristics between events. For example, going from a high-downforce circuit to a low-drag circuit, or altitude changes, which may justify changes in power levels between normally aspirated and turbocharged vehicles.

Reactive changes, made after a performance imbalance is observed, are usually made between race events, but may be made during a race if the need is critical. They must relate back to the scientific process, and be a result of analysis, with data to back it up.

Conclusion

So, at the end of all that, are we any closer to understanding if, and when, BoP changes need to be made?

Well, start by asking yourself, 'what is the primary measure of vehicle performance?' The answer is lap time, and this is where you look for your first clue that something needs to be changed. You are often faced with a dilemma of how fast is fast? Or how much faster / slower is too much? If you take, for example, a lap time delta of 0.1 seconds in a 100-lap race, a vehicle with that delta will be down 10 seconds by the end of the race. There is probably enough variability in lap times, pit stop times, traffic, management etc. that this is not too great a disadvantage, but lap times are just the tip of the iceberg. You need to understand *how* each car is making lap time, and *where* and *why* any performance deficits exist. All the while looking out for performance management!

We are dealing with a physics problem and playing with F = ma to balance all the cars

When performing analyses and determining what to change, recall we are working with an application of Newton's Second Law and equations of motion. We are dealing with a physics problem and playing with $F = ma$ to balance all the cars. So, you need to ask yourself what you are trying to balance. Is it cornering or straights? Top speed or minimum corner speed? Fuel stint lengths or refueling times? Or some combination of everything? Also, are you trying to balance professional drivers or amateur drivers? Or are you trying to make the cars easier to drive so amateur drivers can close the gap between themselves and the pros?

Yes, you will find there are often more questions than answers but, if you follow the scientific method for the BoP process, you will come out ahead.

In the FIA World Endurance Championship, manufacturers agreed an automated BoP system for all races bar Le Mans (pictured), which remains manually adjusted


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Tom Coronel swaps his WTCR programme for the now Saudi Arabia-based Dakar rally. Contesting it with his twin brother, Tim, they share some of the secrets of their 2021 contender

By ANDREW COTTON

Enter the sandman

The cockpit of the Beast is functional for desert running in Saudi Arabia

The Dakar rally has undergone many different incarnations since it first ran in the 1970s, moving around the world until last year, when it settled in the Saudi Arabian desert. Held over 12 days, the rally retains its traditional adventurous spirit and the stages encompass rocks and long sand runs at high speed, but the idea of moving through countries in an orienteering extravaganza are gone for now.

Remaining in just one country has actually helped the organisation with the current Covid restrictions and allowed the rally to go ahead. Drivers will have to quarantine for five days, receive two negative tests and be confined to the bivouac until they are ready to start. In developing their anti-Covid plan with the local authorities, the rally organisation will benefit from experience gained on the Tour de France.

Tom Coronel, more widely known for his circuit racing exploits, has contested the Dakar rally seven times, while his brother, Tim, has competed so many times he has the moniker 'Legend' alongside his name on the entry list. In their workshop in Huizen, Holland they have developed their vehicle for the race. Labelled the Beast347 4.0, it is based on a Baja chassis from California-based Jefferies Racing, adapted to Dakar spec by the Coronel team.

The twins will compete in the Open class of the car competition. There are five categories from which to choose, including cars, trucks, bikes, quads and side-by-side buggies. The car section is split into sub-categories, including T1 for prototypes (and from which, traditionally, the overall winners emerge), T2 for production-based ATVs, T3 for prototypes powered by motorcycle engines – which was the class contested by the Coronels until 2017 – and Open, which includes American SCORE vehicles and can also include electric or alternative fuels.

Gruelling challenge

The Dakar moved from its temporary home in South America to the Saudi desert in 2020, but this year's event is a far more ambitious layout even than last year's. With total daily mileages topping 800km, the rally is a gruelling challenge for both competitor and machine. It starts and finishes in Jeddah, and the route loops around almost the entire region, encompassing Wadi Ad-Dawasir, Riyadh, Buraydah and Sakaka before heading for the coast at Neom, Yanbu and then arriving back in Jeddah city.

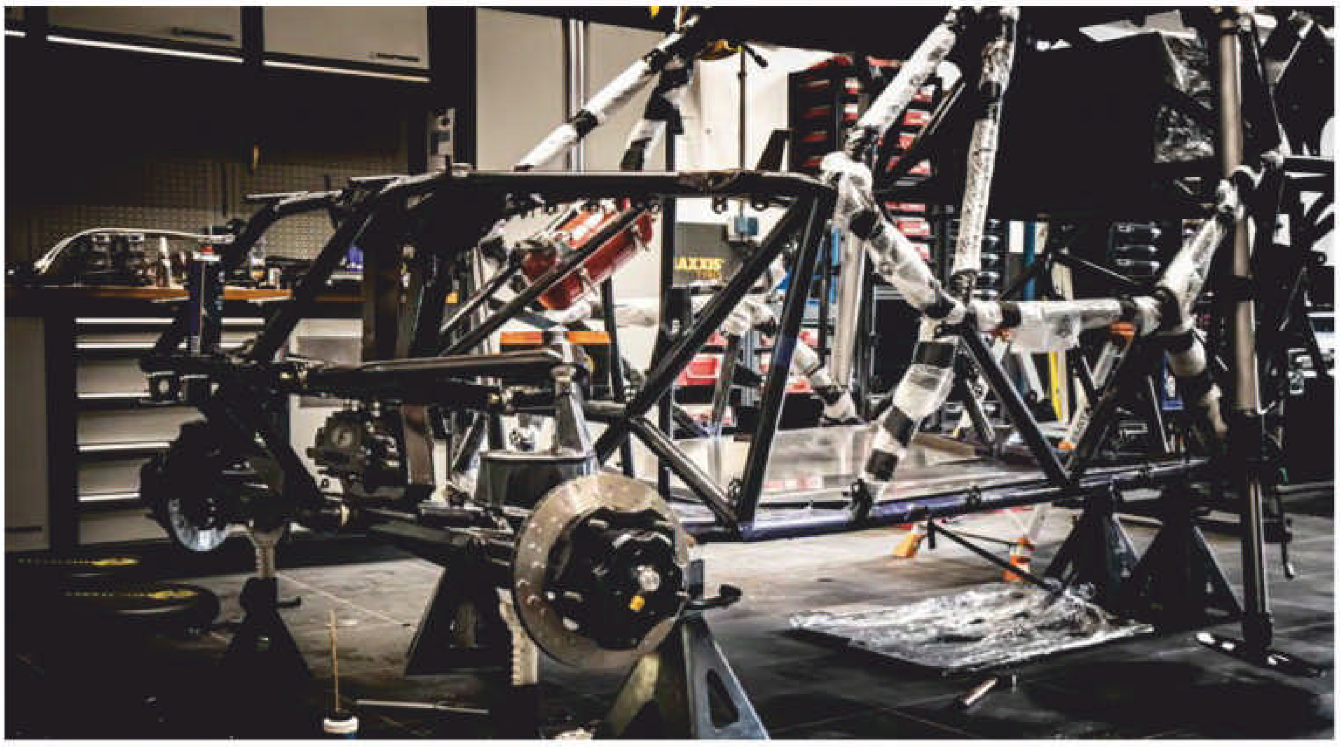
The Coronel Dakar Team received its chassis in March 2020 and, despite Covid restricting working conditions, a team of 14 prepared it for the competition. Compared to the Baja events, which are held over one day, the demands on the car are pretty much polar opposite for the Dakar, and the Jefferies chassis has had to be adapted accordingly.

The first job was to take off the Baja-spec rear end as the weight distribution was all wrong for the Dakar and it needed a major re-think in terms of systems layout.

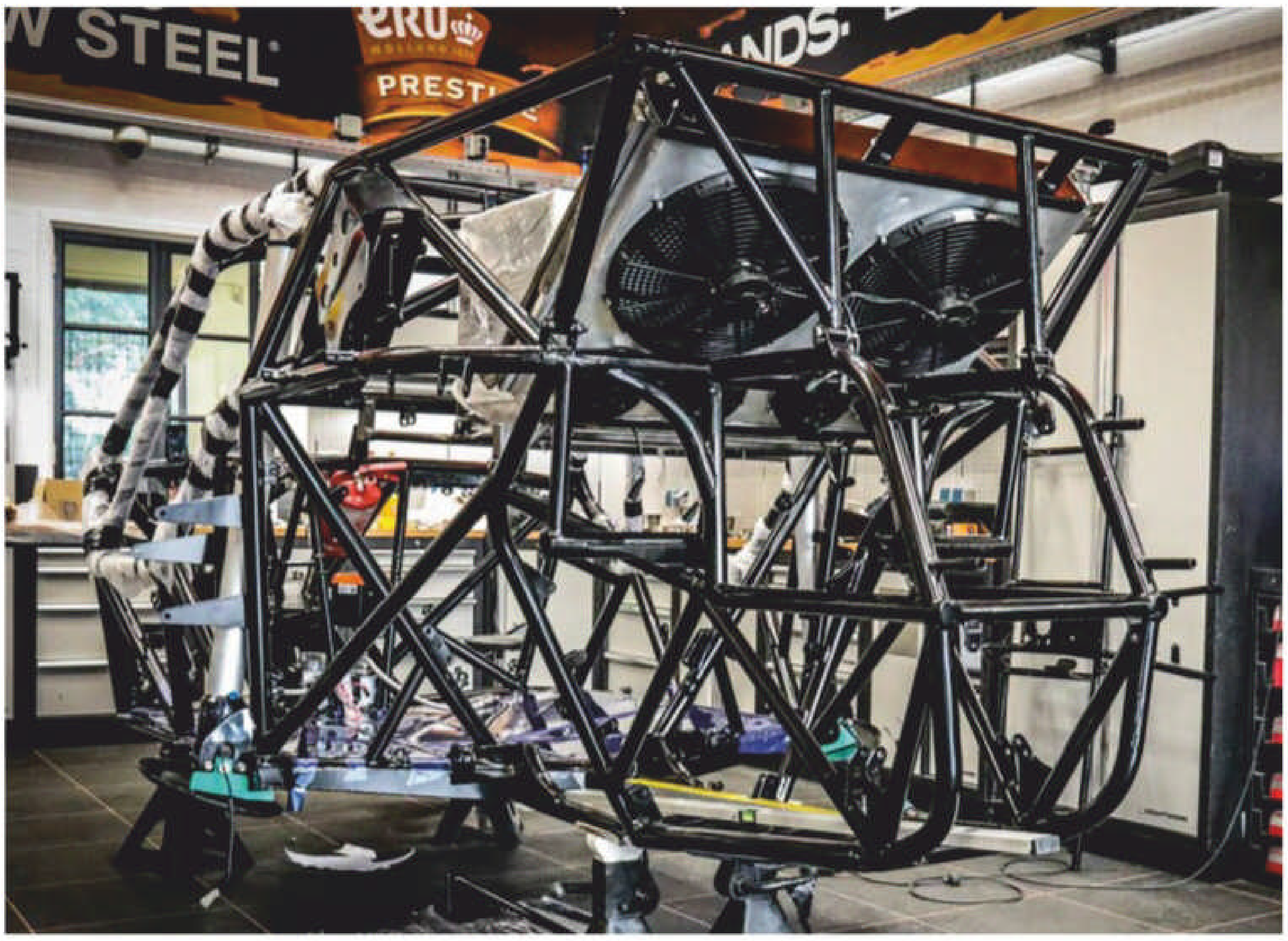
'We didn't need the length,' confirms Tim Coronel, who also takes on the role of lead engineer in the build process. 'We took five or six metres of tubes out of the car, and moved the spare tyres from the rear to the middle.'

Losing so much weight and length from the rear end of the car meant everything, including the fluids carried over the rear wheels, had to be relocated.

'In the Baja, they always want it to be planing like a boat, so they want the weight at the back. That's why they put the tyres and fuel cell there,' explains Tim. 'For Dakar, it is more technical, so you want the weight in the middle and as low as possible, so we made a Dakar car from a Baja car.



Week 1: Front end of the Jefferies chassis was left largely unchanged, and provision made for 65cm front suspension travel



Week 1: Chassis was heavily modified at the rear, removing 5-6m of tube and reducing length to better suit Dakar conditions

Week 1: Fuel tank and fluids are mounted high up for rollover protection

In the Baja, they always want it to be planing like a boat, so they want the weight at the back… For Dakar, it is more technical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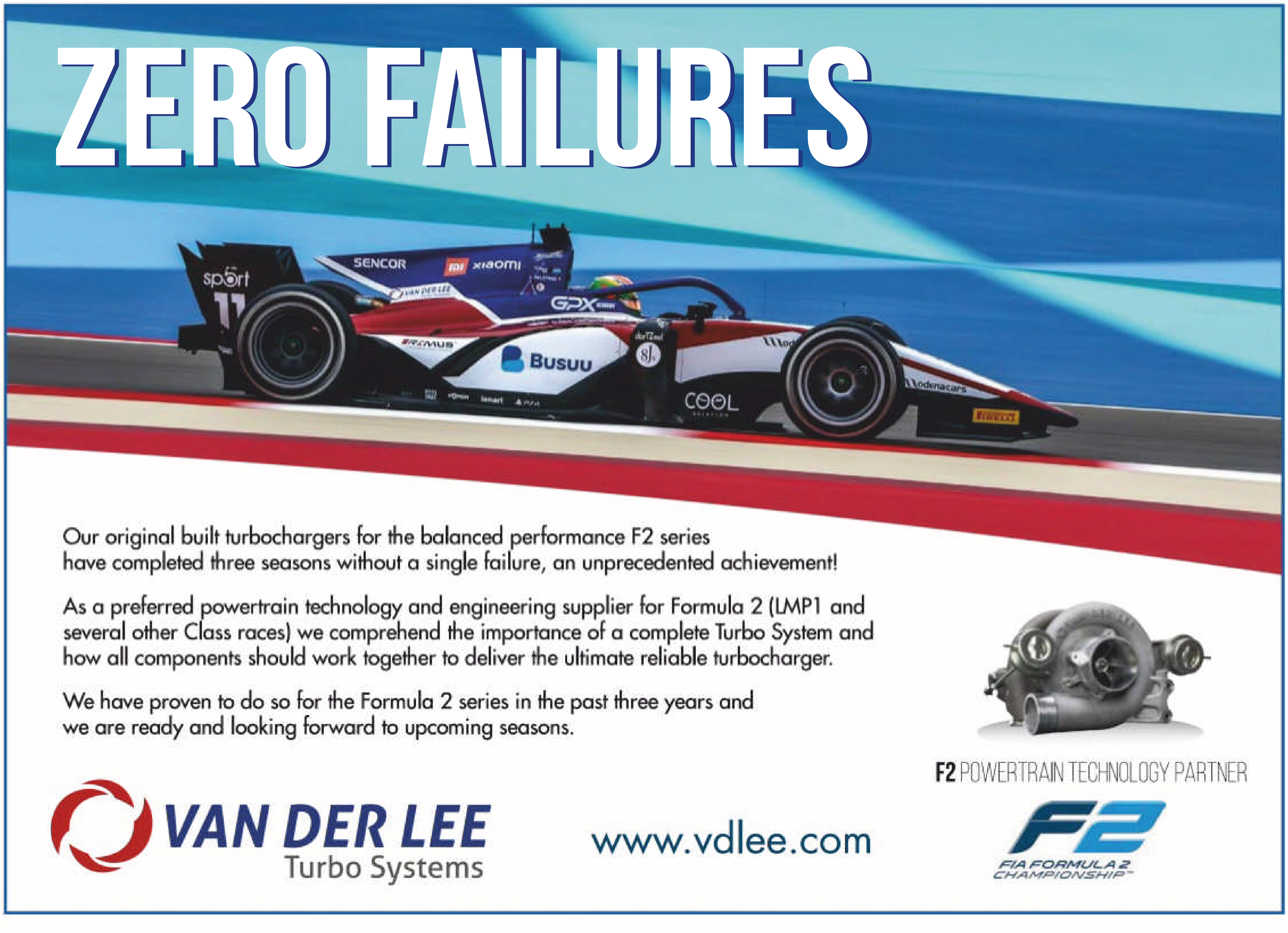
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All the fluids are outside the head cage because then it doesn't matter if you flip the car

'Baja is also only one day, and the Dakar is 12 days, so it needs to be easy to change sparks, or put on the grease, because everything needs to be easy to reach and to fix. That's what we changed.'

Fluid exchange

Consequently, all of the fluids were moved to the middle of the car, including the fuel tank that is now housed right at the top, behind the cockpit. It is protected by the rollcage, so the brothers are not worried about damaging it in case of an accident, as they had last year on their way to 27th place overall at the finish.

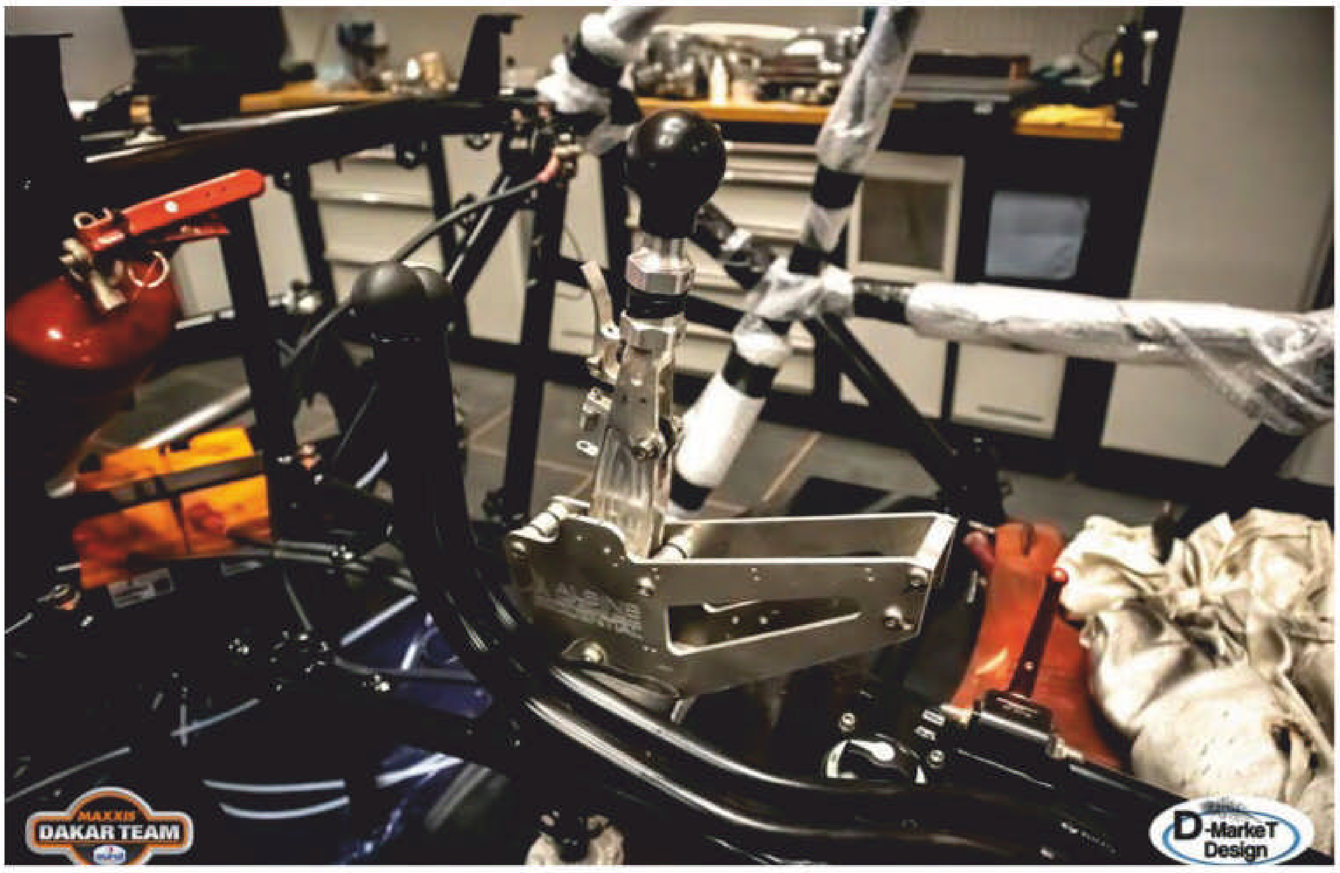
Moving the fluids to the top of the car might not seem logical when it is desirable to have weight low down, but the team calculated that moving them there would help with cooling. 'All the fluids are outside the head cage because then it doesn't matter if you flip the car, you still have a lot of surface [to protect the tanks],' says Tim. 'We don't have a lot of surface [at the back of the car], so everything that we have we put in the roof is within the rollcage. Now we have put them in front of the radiator, which has several advantages, not only in terms of temperature control, but also for the centre of gravity of the car.'

By relocating the tanks to the centre of the car, the entire fluid system needed to be replaced and the twins took the chance to replace the metal hoses from the Baja car with those made from Dyneema, a further weight saving that took even them by surprise.

'We gained a lot on the fluid lines,' confirms Tim. 'The military use Dyneema for bulletproof vests. It is strong and light, so we gained 18kg just with the new materials used for the lines. [In terms of the development for the car] we worked hard on weight and ergonomics to make it easier for the mechanics, or us, to change it.'

Incredible diet

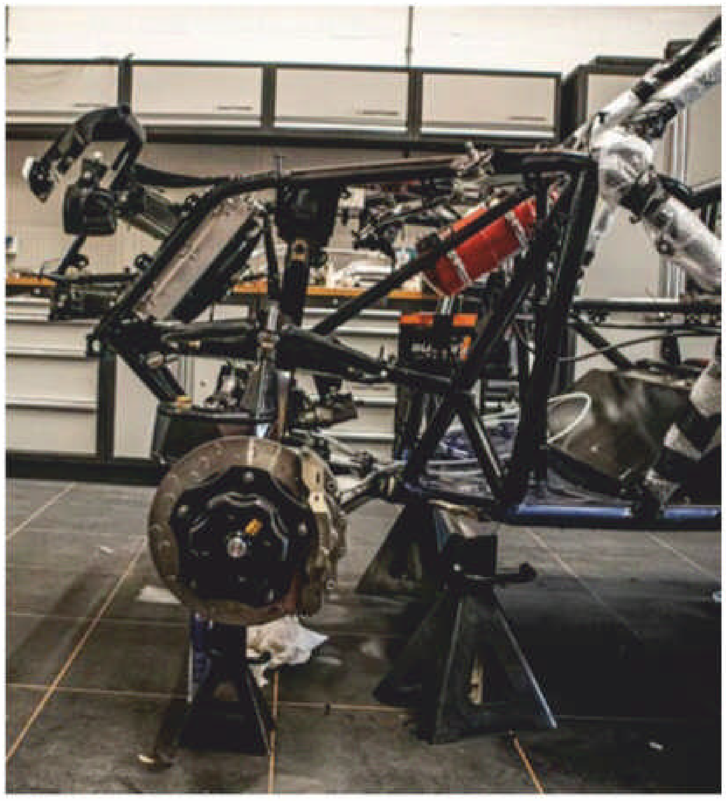
Weight saving was clearly at the heart of the entire build process, with everything carefully calculated. The reduction in chassis volume, as well as making parts from titanium, put the car on an incredible diet. The brothers targeted a weight loss of 100kg but, by the end of October, figured they had reduced the car's weight by 140kg. Even they were



Week 3: Gear shift mechanism and converter are by Albins

TECH SPEC: Dakar Beast 4.0

Body style	
Mid-engined Rally Raid car	
Chassis:	
Chromoly tube chassis; rear-wheel drive; independent suspension; SCORE regulations build	
Motor	
Make:	GM LS3
Type:	V8
Capacity:	6.2 litres
Max power:	approx. 410bhp at 4300rpm with regulation 37.2mm restrictor
Max torque:	600Nm from 3000-4700rpm (with regulation restrictor)
Transmission	
Sequential six-speed; Albins converter	
Suspension	
Front:	Independent; adjustable coil spring / damper units from King Shocks
Rear:	Independent; adjustable coil spring / damper units from King Shocks; anti-roll bar
Steering	
System:	Hydraulic power assisted
Brakes	
System:	Hydraulic, adjustable dual circuit
Front:	Alcon – ventilated discs; six-piston fixed calipers
Rear:	Alcon – ventilated discs; four-piston fixed calipers
Wheels and tyres	
Front:	17in beadlocks with 37 x 12.5-17 Maxxis TL M8060 Comp 124K
Rear:	17in beadlocks with 37 x 12.5-17 Maxxis TL M8060 Comp 124K
Dimensions	
Length	4600mm
Width	2300mm
Height	1800mm
Track,front	2200mm
Track, rear	2200mm
Weights and capacities	
Dry weight	1412kg
Fuel tank volume	430l safety tank


Week 3: Rear suspension, cooling and ancillaries fitted

The brothers learned from 2019 and while the new car retains the centrally located spare wheels of last year, they are further forward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We don't care about anything else, we just want to jump

surprised then when they weighed the full car at the end of the process in December and found it to be 200kg less than the original base weight of the car. They even went back and checked their scales to make sure they hadn't made a mistake.

'Every detail on the build was based on weight,' interjects Tom. 'Bodywork, hoses, every screw. We even have kitchen scales to measure the smaller parts. It was quite an expensive process because pretty much everything now is titanium.'

Even the carbon bodywork went on a diet. With the help of Dutch specialist, Van Thull, the thickness of the body panels was reduced from five layers to three, or even two in some places, in order to save vital grammes. The brothers also shortened the bodywork to help the car's handling in the sand.

'Last year, we noticed during a sandstorm that the side winds had quite a big impact on the car,' remembers Tim. 'For that we found a solution, and the chassis and bodywork has been shortened a bit.'

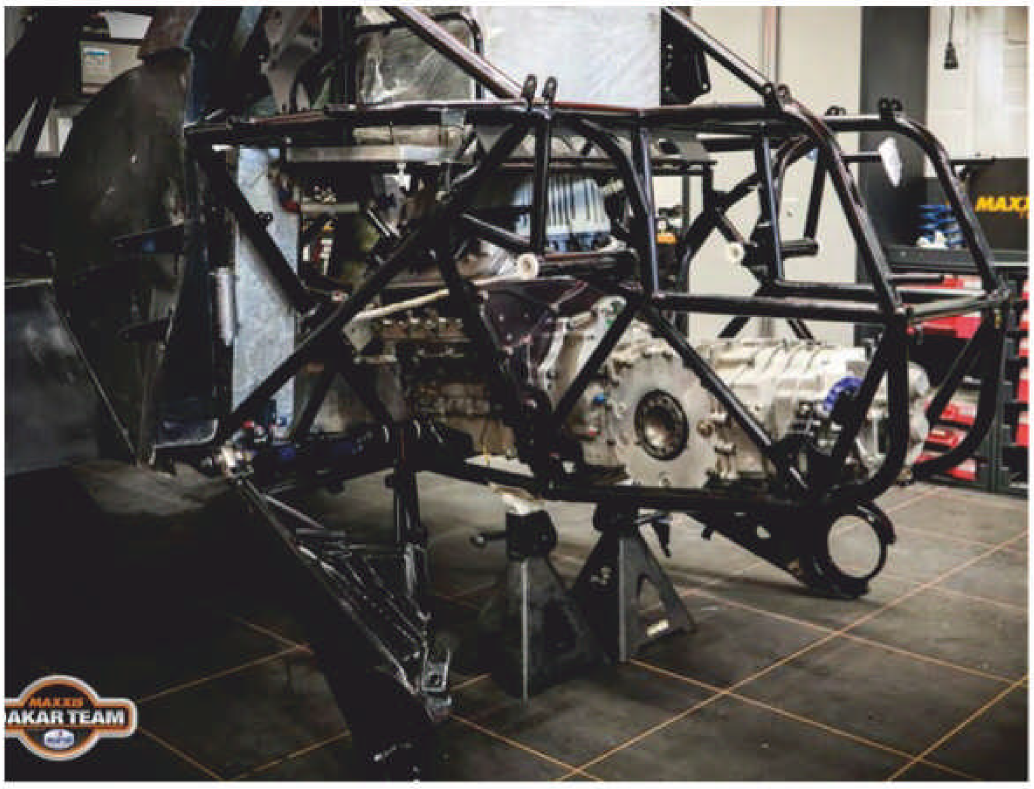
Engine development

One area they didn't compromise was the engine, and team Coronel Dakar stuck with the tried and tested GM LS3 that had proven so reliable in the past. The engine has been developed on the test bench since early in May, and the brothers believe they have found quite an improvement in performance. A slight improvement in fuel consumption will help to further drive down the weight of the car, but the development focussed on increasing the power band to improve top speed, which they felt was lacking in 2020. The brothers figured they needed more torque and higher revs to be competitive, but had another obstacle to overcome in the shape of the regulations.

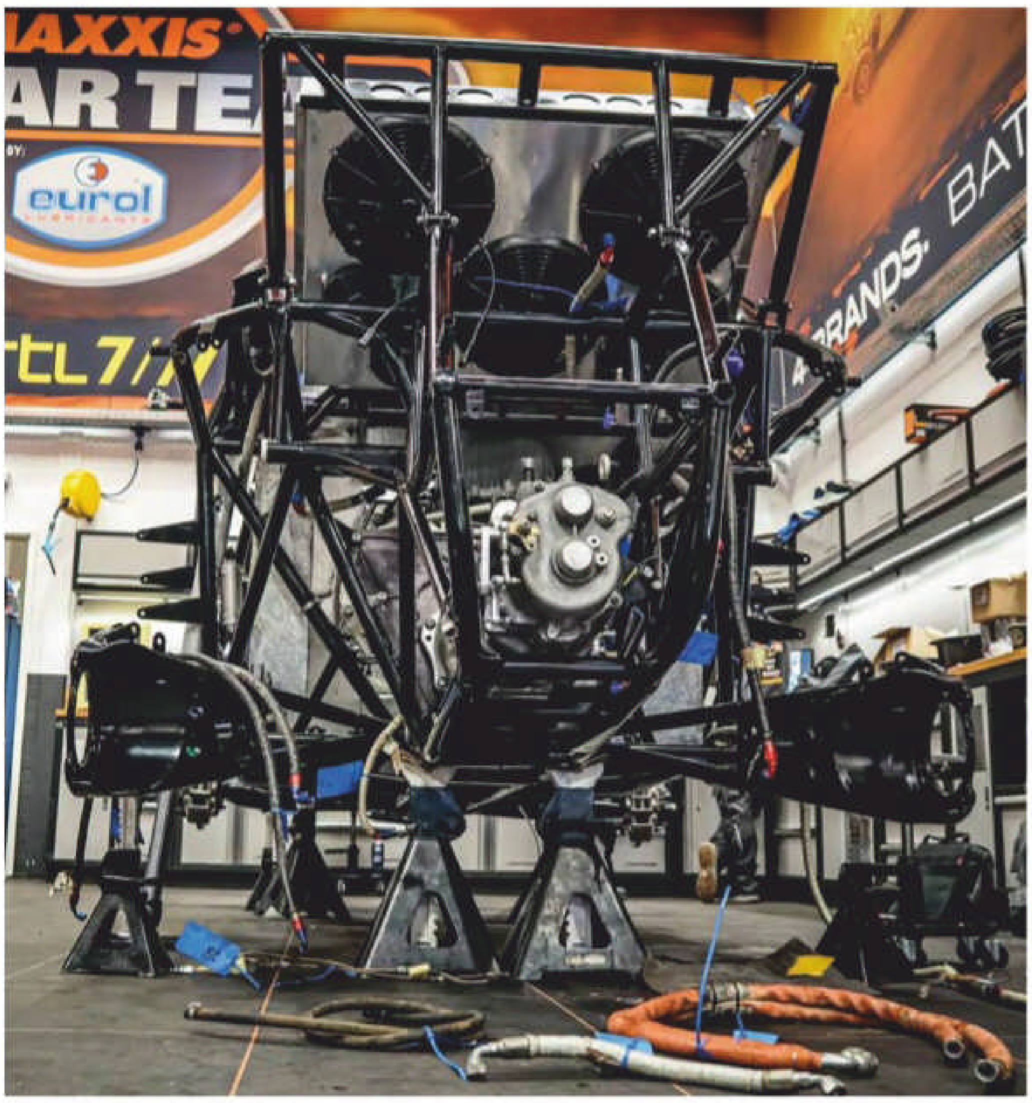
'Normally, we have a restrictor of 39mm and now we are only [allowed] 37.2mm, so it is smaller than my dick,' quips Tim. 'We had to take another intake, but we also did a lot of work on the bench with APP engines, and we found more torque, power and revs.

'Last year, the torque went away at 4300rpm, so we could only do 165km/h and you need to do 190-194km/h. But then you also need more torque, to 4700rpm, and then you can go further.'

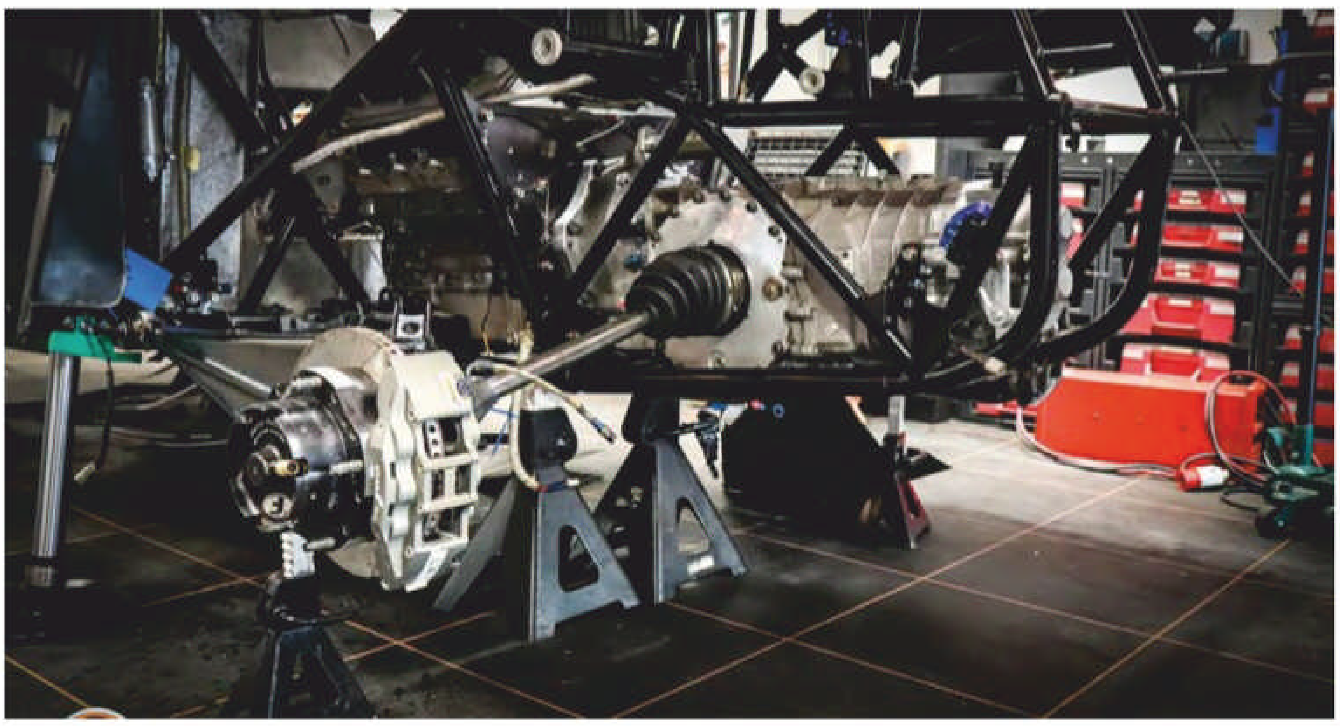
Hampering their quest more, the engine development team were not allowed to change the ECU. 'We are only allowed a stock engine,' laments the Dutchman.



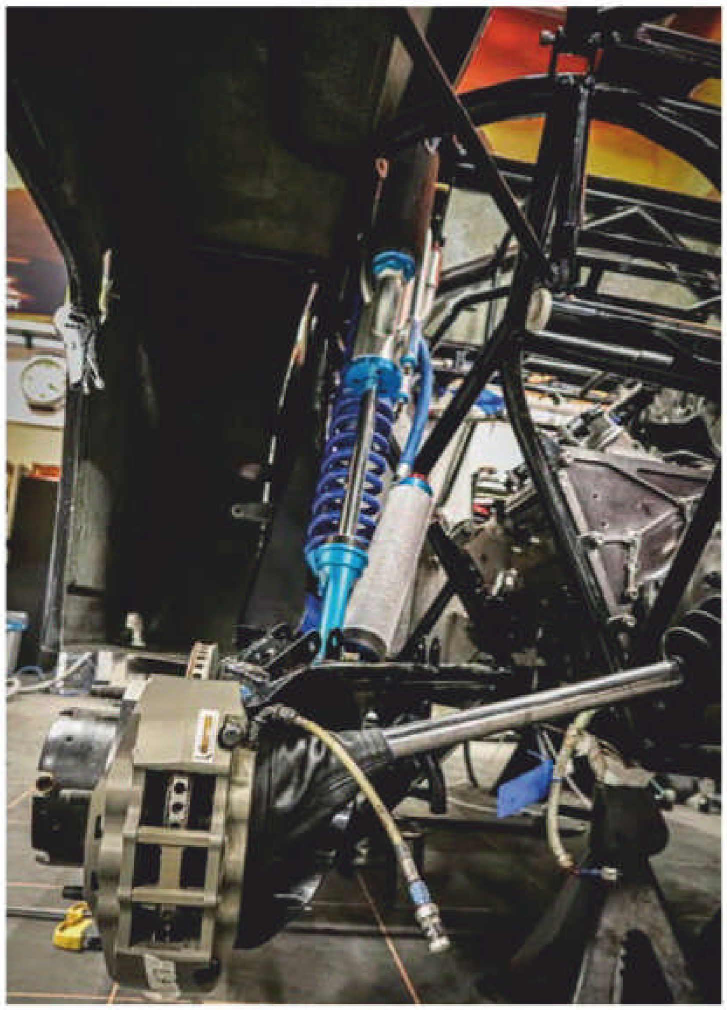
Week 5: installatiopn of the GM LS3 V8, which produces around 410bhp and 600Nm of torque through a regulation 37.2mm restrictor, and sequential six-speed transmission



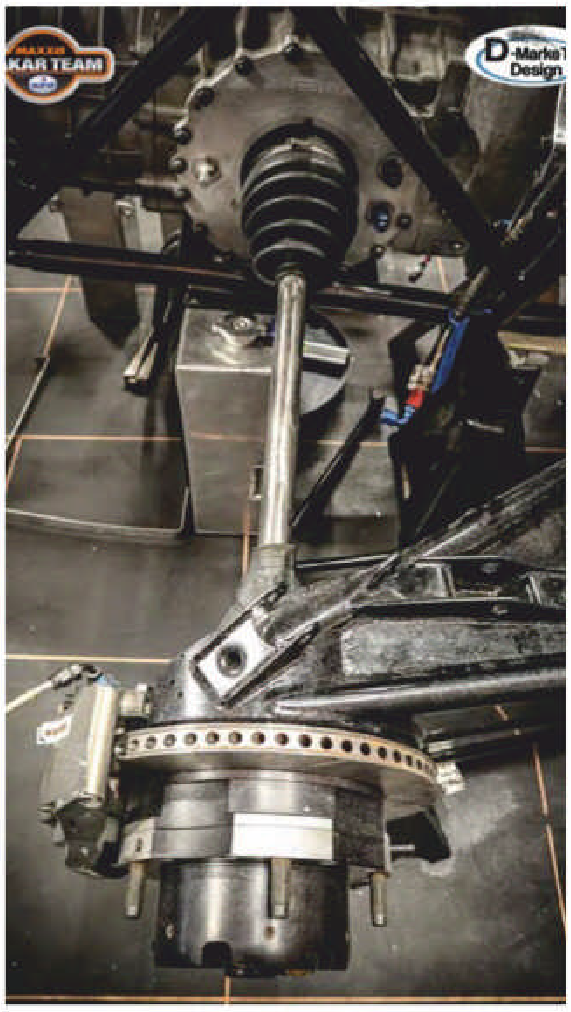
Week 6: A late decision to change the fluid lines from metal to Dyneema yielded an astonishing 18kg weight saving



Rear suspension droop is less than on a Baja version of the Jefferies chassis due to the mandated angle of the rear dampers



Week 8: King Shocks supplied Trophy Truck-style spring / dampers



Week 9: Alcon disc brakes are used front and rear

Week 10: The Beast almost complete and race ready, weighing in at 200kg lass than the original base weight of the chassis

Week 11: The lightweight carbon bodywork, reduced to the thinnest skins possible by Dutch company Van Thull, goes on

One of the major development areas on any off-road vehicle is, of course, the suspension. Not only does the car need to be able to climb rocks and be robust and stable enough to survive doing so, it also needs top speed for the sand sections. The team turned to King Shocks for their needs this year, and the company did not disappoint, delivering racing shocks with enough travel to cope with the demands of the Dakar.

Trophy travel

'The travel is 65cm at the front, which is a lot,' says Tim. 'We wanted a Trophy Truck shock because you always want the wheels on the ground and we want to jump. We don't care about anything else, we just want to jump, but the longer the travel the better because in the dunes it is easier when the tyres are on the ground.

'On the back, we are limited in terms of suspension travel because of the angle of the shock. That can only be 28 degrees, so we have 55cm of travel there. In the Baja it is 65-85cm because they have only one axle linear from the back, but we don't have that.'

The Maxxis tyres are the best the brothers could have hoped for and are custom made for the twins. Kevlar sidewalls help protect against punctures, as is standard, but the company went all out to develop rubber specifically for this challenge.

'I am working with the technical guys and they stopped the whole production line to make the tyres for us with the Kevlar. We are full in, flat out,' concludes Tim.

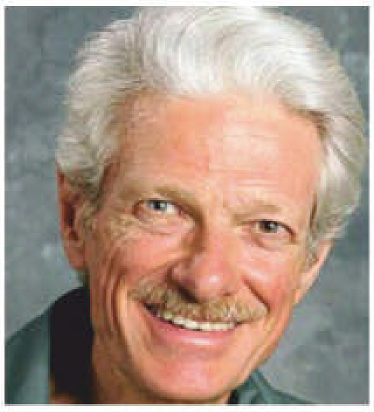
The rally starts on January 3 with 75 cars, 42 trucks, 110 motorbikes and quads on the start list. Along with the vehicles required to run the rally, that's a total of 679 machines, plus eight helicopters and 15 containers. It's going to be quite the spectacle.

Into the future

The 2021 edition of the Dakar rally sees the rise of a new breed of pioneers developing low-emission electric vehicles capable of winning the rally. Audi announced it will join the category in 2022 with an electric prototype powered by a high-voltage battery that can be recharged on the go.

Five-time winner, Cyril Despres, and his colleague, Mike Horn, are targeting a podium spot in 2023 with a hydrogen-powered vehicle, and will be taking part in 2021 with a Peugeot 2008 to gather data to help with their design.

Meanwhile, Guerlain Chicherit's GCK team will unveil in Neom an electric vehicle currently in development and also with a targeted 2023 entry.



Under the Aurelia

Explaining the rare and desirable Italian car's suspension design

By MARK ORTIZ

Q I recently discovered a fascinating car from the 1950s that I'd never heard of before. It's called the Lancia Aurelia. The car had the first production V6 engine, a transaxle and really interesting suspension. The front was a sliding pillar system that Lancia apparently introduced in the 1920s. There were two different rear suspensions. The cars are rare, but there seems to be a resurgence of interest in them lately, especially in England.

I'd be interested in your thoughts on their suspension systems. What are the pros and cons of sliding pillars? They look to be a simple and elegant solution, but nobody uses them nowadays.

Apparently, the first type of rear suspension was independent, but they later replaced it with a DeDion.

THE CONSULTANT

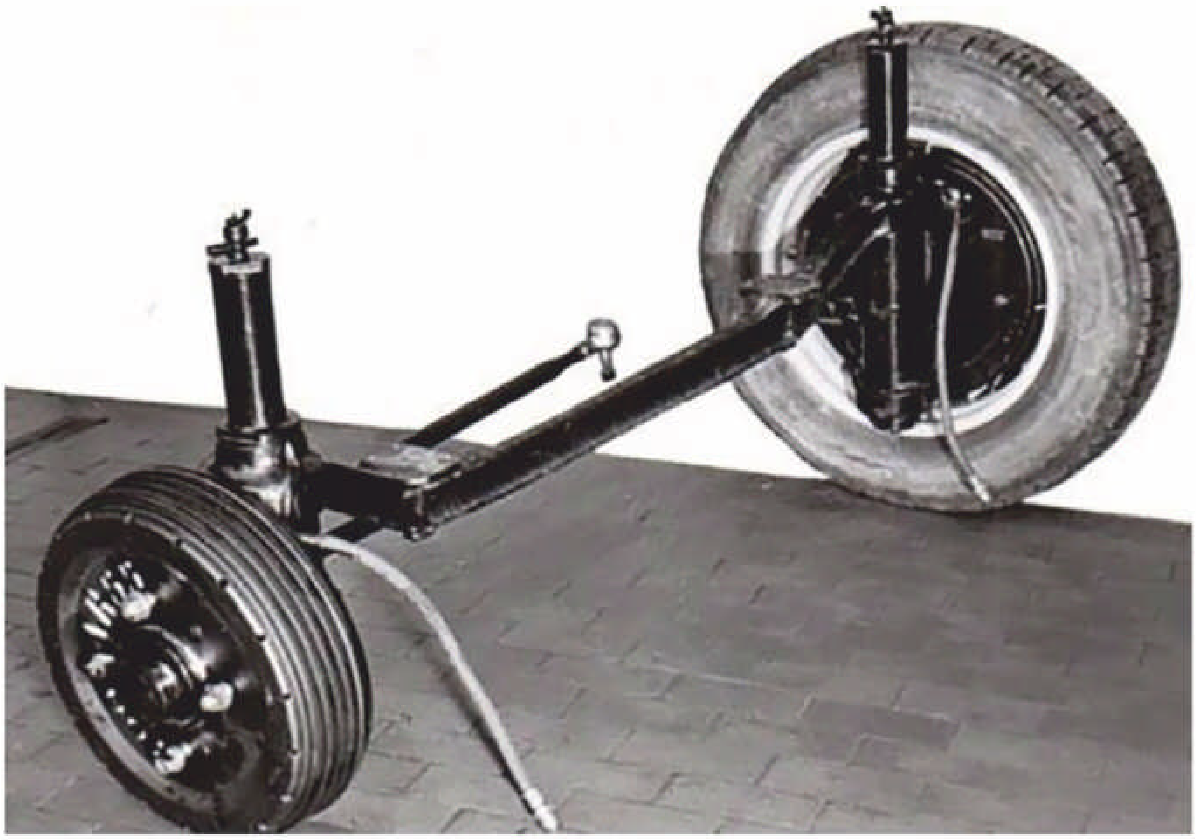
A I was somewhat aware of these cars, but had never studied them as they were not imported in large numbers to the US and remain quite obscure here. However, doing an online search, I found a really nice website created by Geoff Goldberg of Chicago, see www.lanciaaurelia.info.

Mr. Goldberg has reproduced some excellent illustrations from magazines and original manuals, some of which I have shown here, with attribution to the original sources. If you are interested, I would recommend checking out the website.

Sliding pillar suspension is best known from its use on British-built Morgans, but a few other manufacturers have used it as well, mainly as a front suspension. There was a rare model of Invicta, the Black Prince, made in the late 1940s, that used it for all four wheels.

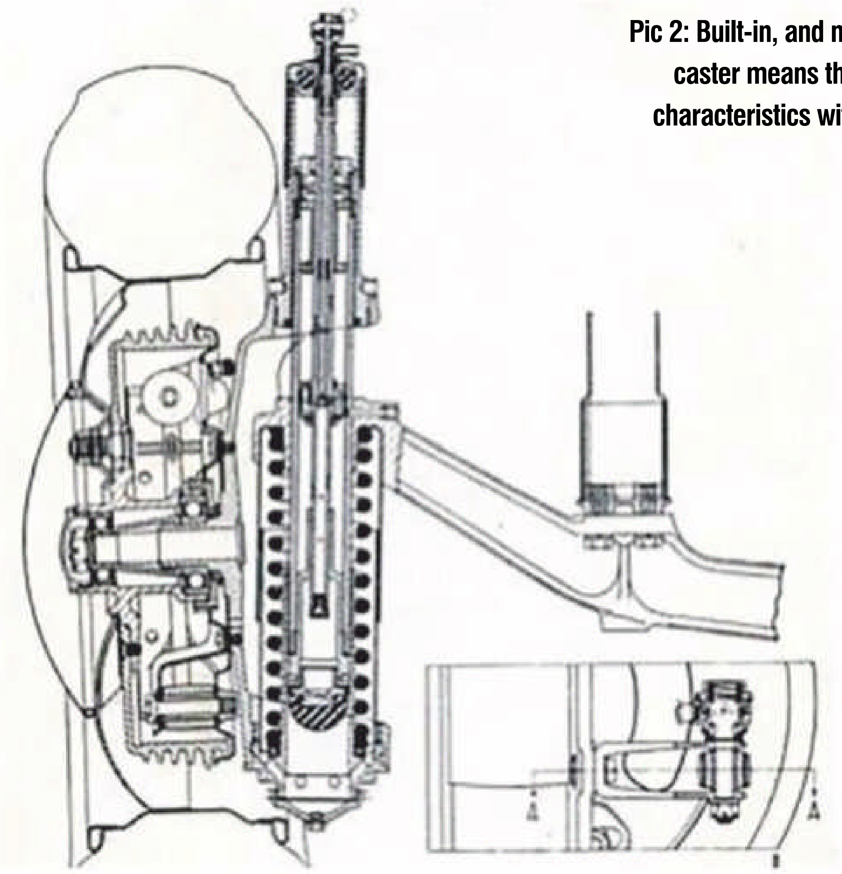
It is usual to use the pillar as the steering king pin, and the Lancia design has an unpressurised tubular shock and a coil spring coaxially built into the pillar unit.

For orientation, in **Pic 1**, we are looking at the front suspension assembly from behind.



Images: Lancia Aurelia homologation documents / *Automobile Engineer*, 1951

Pic 1: Lancia Aurelia sliding pillar front suspension offers minimal adjustment options to tune for handling



Pic 2: Built-in, and non-adjustable, camber and caster means the suspension shares many characteristics with a rigid beam axle design

The shocks are adjustable at the top, and the whole affair is mounted on a removable axle-like, I-beam crossmember. The only available adjustments, other than shock stiffness, are toe, via a one-piece tie rod (mostly hidden by the crossmember in the photo) and steering centring, via the drag link visible ahead of the crossmember. The Pitman arm attaches

If anything [in the front suspension] gets bent, you either live with it, bend it back again or replace parts

to the rod end shown hanging loose, which tells us this is a right-hand drive car. A Lancia idiosyncracy was that many were sold with right-hand drive, even in continental Europe.

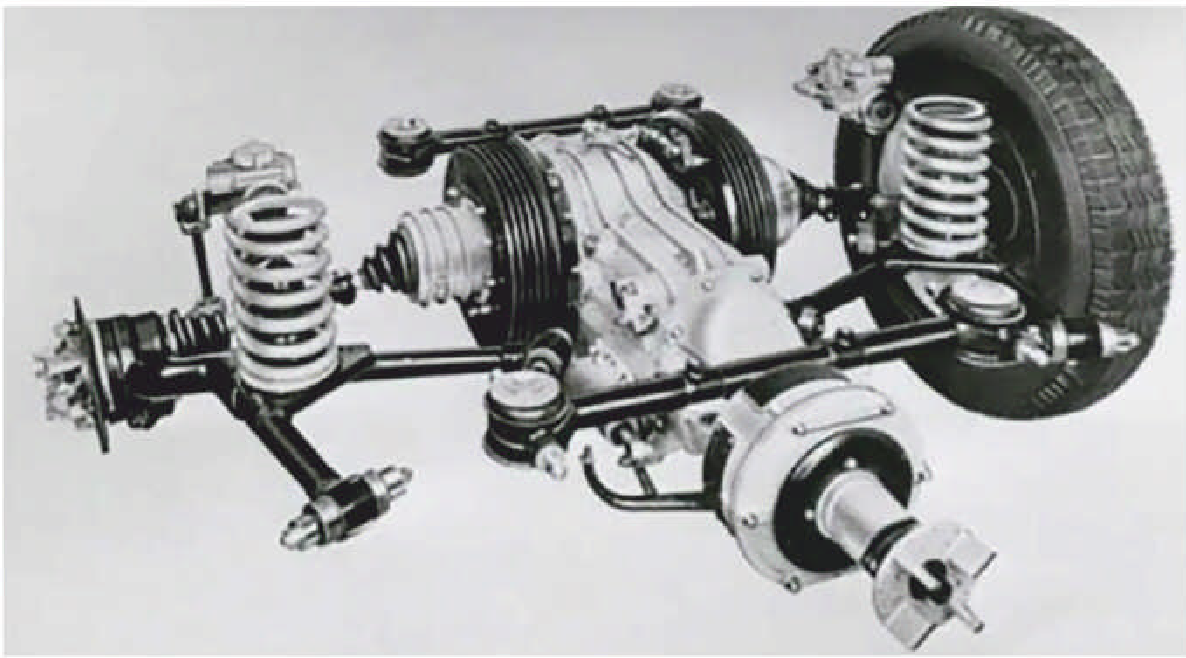
So you don't have to adjust much. Then again, you can't adjust much. The caster and camber are as accurate as the initial build. If anything gets bent, you either live with it, bend it back again or replace parts. Adjusting caster or camber to tune handling is not an option, except perhaps by heating and bending, or maybe shimming at the crossmember mounts. In these respects, it's a lot like the beam axles that prevailed when it originated.

Pic 2 shows a sectional view of the same system. It will be seen that there is very little steering axis inclination and the wheel moves almost vertically. There is a very small amount of geometric pro-roll, or a roll centre just below ground level. The scrub radius or steering offset is considerable for the day, and there looks to be fairly little tyre clearance.

On your toes

As with all sliding pillar systems, there is no camber change in ride or heave, and accordingly no camber recovery in roll. The wheels lean with the body. If there is any caster, there is pro-dive in braking. Caster does not change in heave but does change in pitch, much as camber does in roll.

It is a bit problematic to eliminate bump steer entirely. The usual approach is to use a single tie rod and as long a drag link as packaging allows. This will give zero toe change in ride or heave but a little steer of both wheels together. In roll, the fixed tie rod length will produce a little toe change wheel to wheel. If we convert to rack and pinion steering, bump steer will be worse than stock if the rack has the usual short tie rod to each steering arm, and no other tie rod. It will be possible to get the bump steer instantaneously zero at static ride height, and the car will probably be driveable, but a better approach might be to mount a structure to the rack ends that carries the rocker of a Watt linkage, and retain a long tie rod from one steering arm to the other. The two links of the Watt linkage would go to the steering arms, just like the drag link in the stock setup goes to one. Even then, there would still be a little toe change in roll.



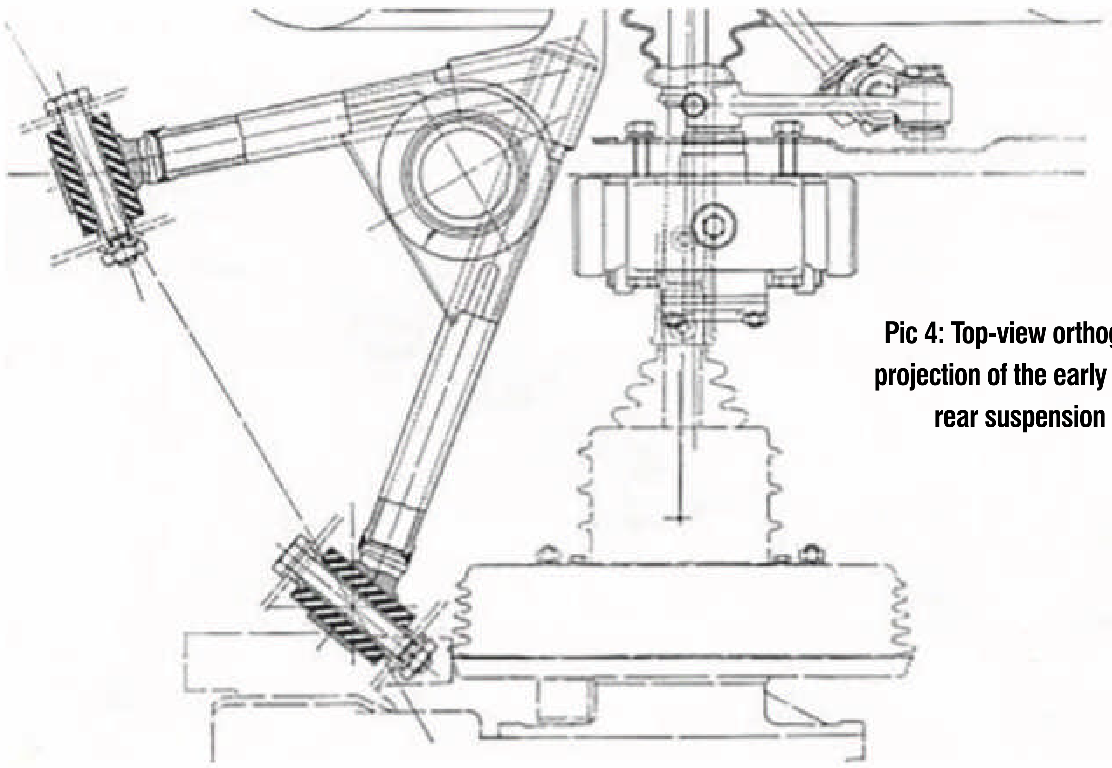
Pic 3: Lancia initially used a semi-trailing arm rear suspension, but it was prone to jacking and snap oversteer

Now, the rear suspension. **Pic 3** shows Lancia used technically a semi-trailing arm system, but with such short front view swing arms that they acted much like swing axles. On the Lancia, it is less than three quarters of the track width, and the arm's pivot axis does not pass below the axle line significantly. That means the roll centre is more than two thirds of hub height – enough to produce fairly serious jacking and snap oversteer.

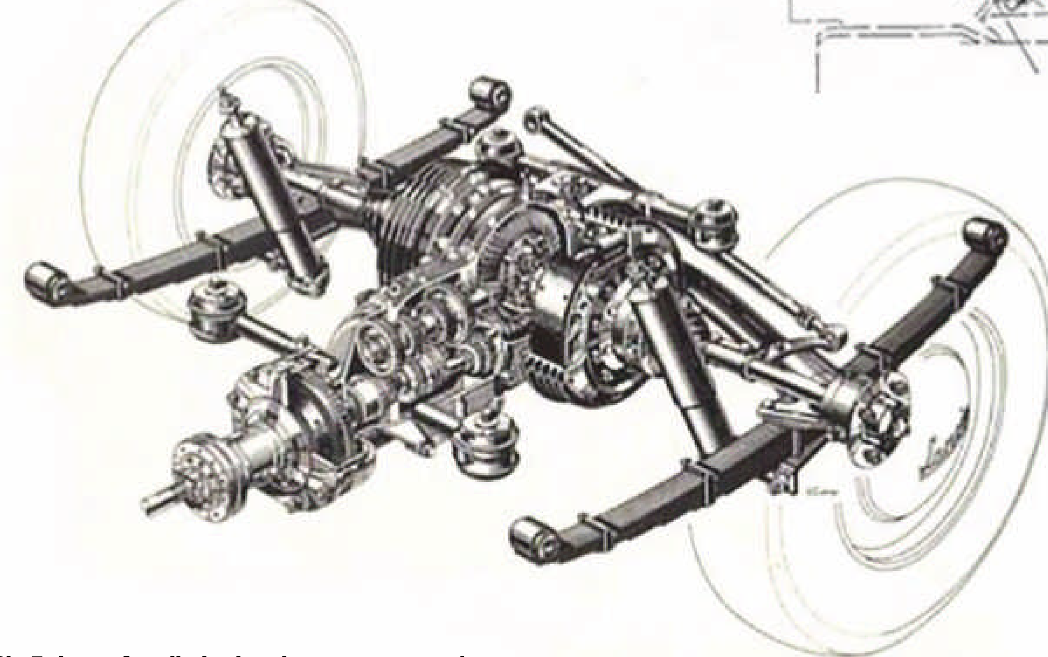
Each arm's pivot axis passes roughly through the opposite wheel's inboard CV joint centre, so the system is like a swing axle layout.

Pic 4 is a top-view orthographic projection.

In 1954, that layout was replaced with the one shown in **Pic 5**. The use of leaf springs is interesting, and actually makes considerable sense in this application. With the inboard brakes and sprung differential, no torque is transmitted through the springs, and spring wrap-up is therefore not a concern.



Pic 4: Top-view orthographic projection of the early Aurelia rear suspension system



Pic 5: Later Aurelia leaf spring rear suspension

CONTACT

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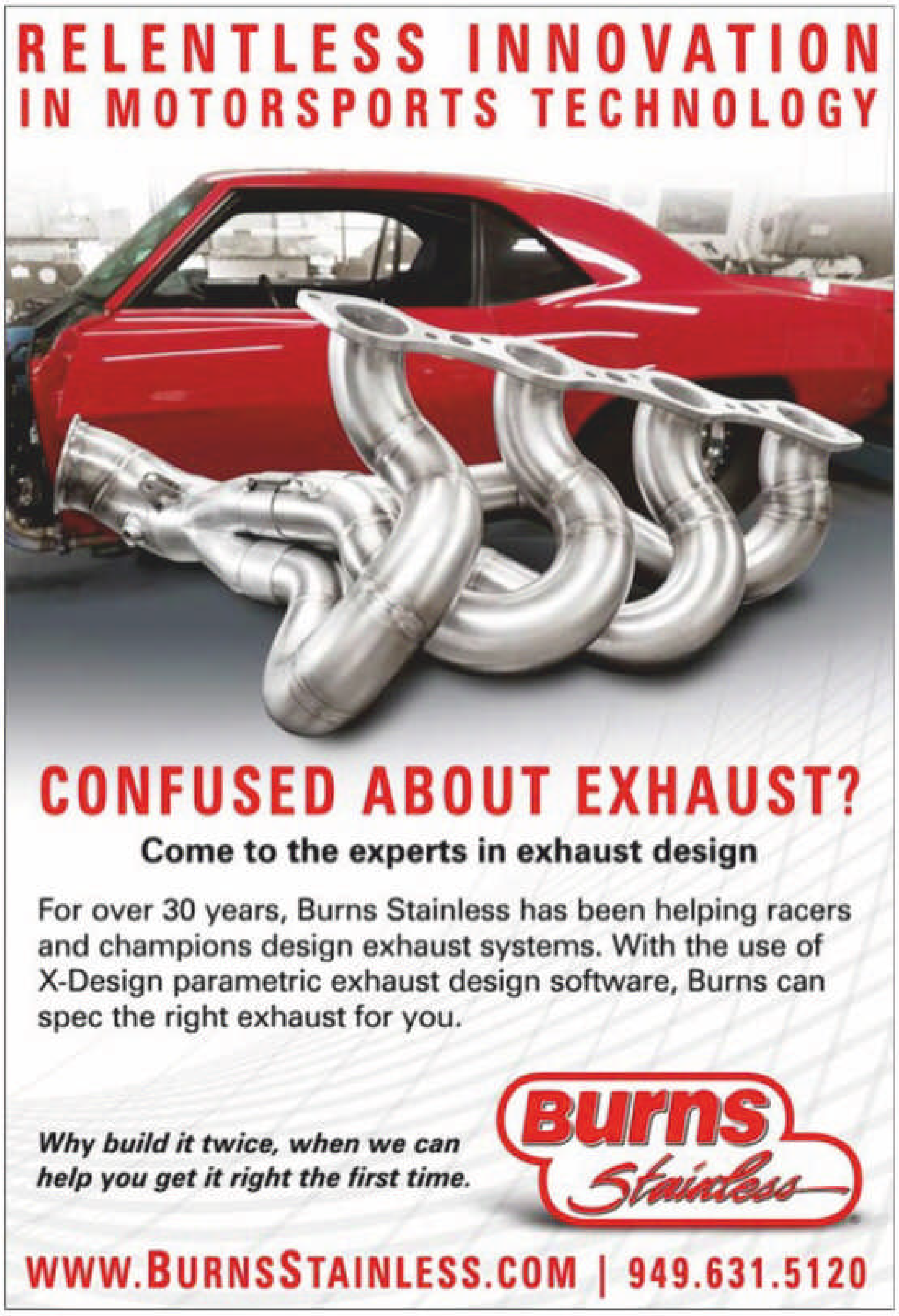
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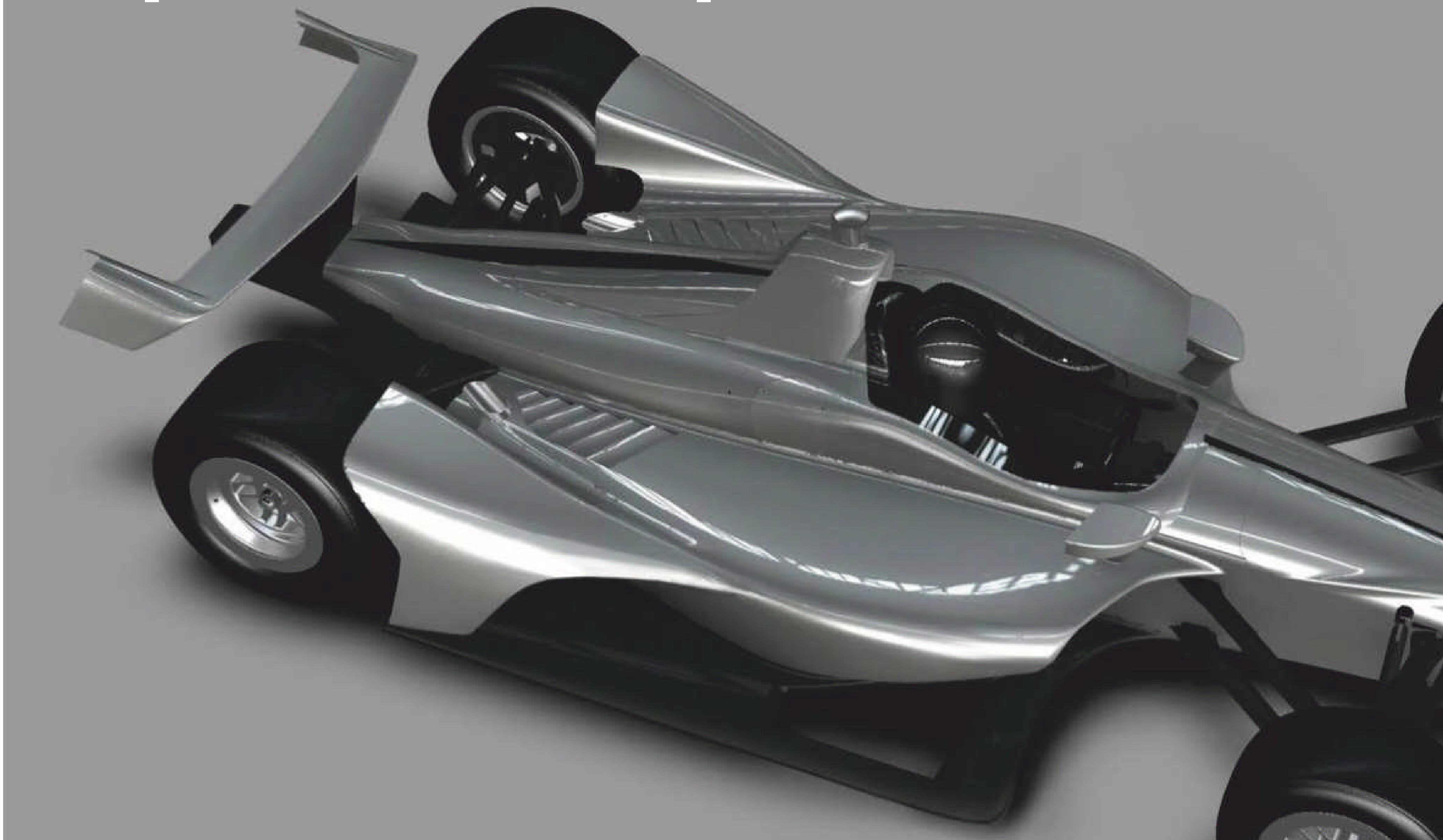
Speed trap



Making the current IndyCar both *look* fast *and* hit its performance targets was a delicate balance of engineering and aesthetics

By CHRIS BEATTY

There had been several runners in the race to land the 2012 IndyCar chassis supplier contract, including concepts from Reynard, Lola and Swift. The extraordinary looking Delta Wing was also in the mix for a while, but was perhaps a step too far out of the traditional comfort zone for some. But in July of 2010, IndyCar announced that Italian racecar manufacturer, Dallara, had been awarded the contract to replace the series' ageing IR-5 chassis with a new vehicle titled the IR-12.

Dallara had been sole supplier of chassis to IndyCar since 2007 with the IR-5, which was a development of the IR-3 and had become the weapon of choice for teams, pushing out Panoz at the end of the 2006 season.

The IR-5 served the series well but, as always in motorsport, there was a need to progress and further enhance driver safety. IndyCar's intent was to produce a next-generation safety cell, drawing on Dallara's extensive experience in the series, and the wider racing industry. The chassis was designed to allow the upper surfaces of the car to be swapped for updated parts as both Dallara and IndyCar refined the aero package.

Dallara worked with IndyCar legend, Dan Wheldon, while testing the IR-12, with Wheldon providing invaluable feedback to the engineers and designers refining the car ready for manufacture and customer delivery. Such was Wheldon's contribution, it was named the DW12 in his honour following the Las Vegas accident that cost Wheldon his life and rocked the sport to its core.

For 2012, the car was to run in a spec-format Aerokit, with power coming from Lotus, Honda and Chevrolet. Initially, the intention was to open up development of the attached aerodynamic surfaces to multiple manufactures such as Lockheed Martin, GE, Lotus and Chevy for 2013, but this was rejected unanimously by the teams on the grounds of increased cost. However, in 2014-2016 the regulations were changed to allow the development of manufacturer Aerokits in an effort by series' bosses to open up the engineering innovation of the car's development, and add another competitive facet for series' engine manufacturers, Chevy and Honda, to generate individual aerodynamic packages.

The dawn of DW12

In March of 2012, the DW12 made its debut on the streets of St. Petersburg. The car met with a mixed reception, many fans taking a particular dislike to the new bumpers behind the rear wheels. The intention there was to

Developing the DW12 chassis to achieve different goals has seen a wealth of experimental design work since 2012

The [DW12] design looked stretched, and seemed to lose part of the personality that had been key to American open-wheel racing for so long

stop following cars 'climbing' over the rear wheels of the lead car in the event of tyre-to-tyre, or nose-to-tyre contact. However, when combined with the DW12's larger tyre ramps, it created a visual effect more akin to a Sportscar, and was one of the critical areas in which the DW12 took a step away from the traditional IndyCar aesthetic.

The design looked stretched, and seemed to lose part of the personality that had been key to American open-wheel racing for so long. Add to this forward-tapered sidepods, a roll hoop cover that leant back in a submissive manner and a high airbox and engine cover, and the result just looked awkward.

That awkwardness didn't stop with the visual either, the weight distribution was biased to the rear, mainly a side effect of the rearward position of the radiators, combined with the new rear wheel pods. The result was tail-happy cars that were prone to reaching the point of no return with even the slightest amount of oversteer.

Add to this the car's initial failure to reach the qualifying target speed of 225mph+ for that year's Indy 500, Dallara and IndyCar found themselves having to play catch up over the month of May. Eventually, with significant Superspeedway bodywork changes and a 0.1bar boost increase, Hélio Castroneves touched 227mph in practice, with Ryan Briscoe taking the pole at 226mph.

In 2015, the regulations were opened back up to allow manufacturers, Honda and Chevrolet, to design and build their own Aerokits. The idea was to give the two marques individual identities by dressing the Dallara chassis with their bodywork within specified 'boxes', or volumes. However, rather than generating compelling personalities for their cars, the designers borrowed heavily from Formula 1's playbook by adding aerodynamic devices wherever they were allowed. The cars went from awkward to ridiculous in their appearance. The road course kits had enormous multi-element front wings, with rear wings that resembled garden fence panels. Additional winglets on top of the now aerodynamically focussed rear wheel pods only added to the cluttered look.

But aesthetics was not the main issue with the 2015-'17 manufacturer Aerokits. The resulting development race produced an alarming cost escalation that forced IndyCar to step in and freeze and further iterations throughout 2017.

Dan Wheldon at the wheel of the IR-12, which was later re-named the DW12 in his honour

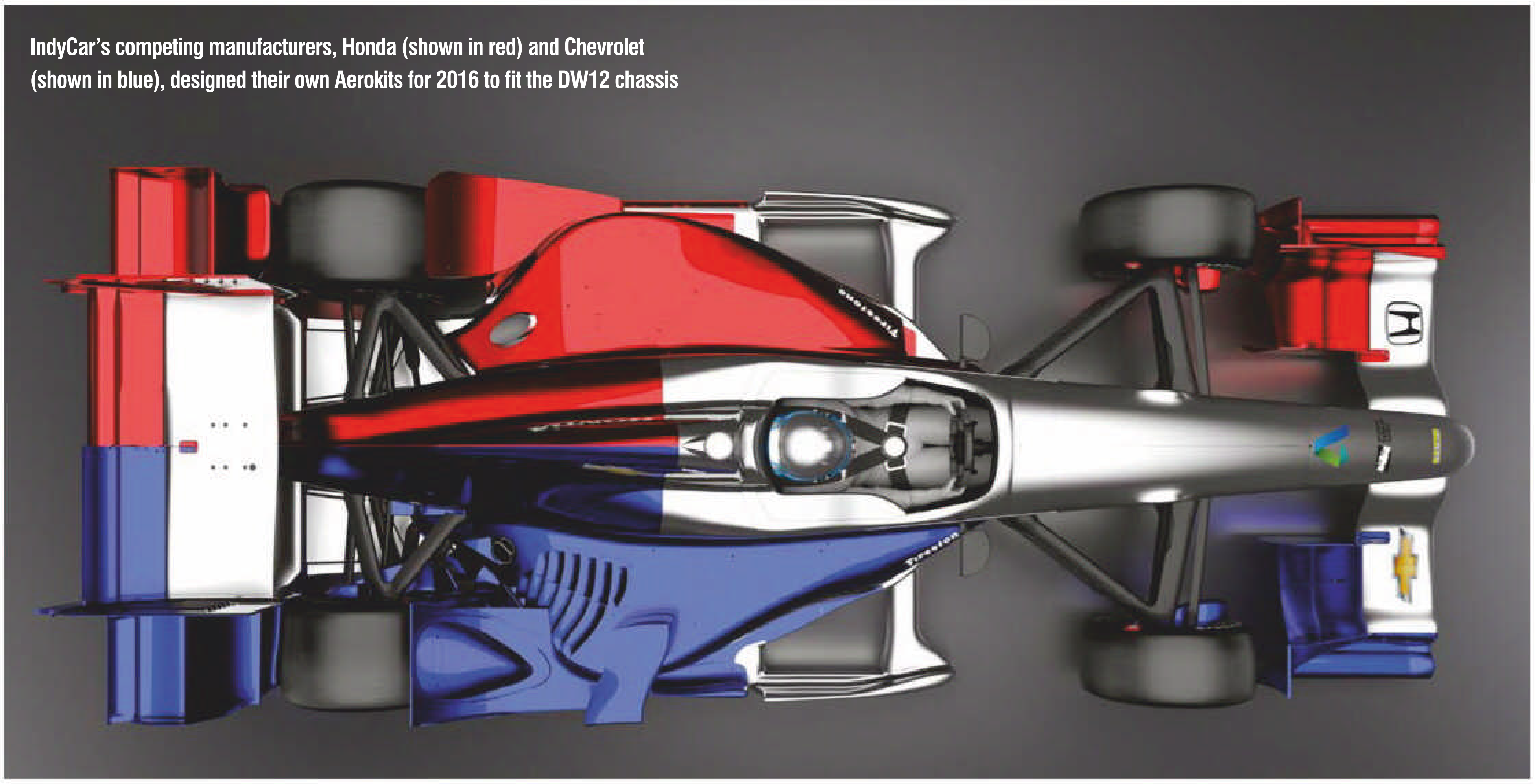
Universal Aerokit

In 2016, IndyCar's president of competition, Jay Frye, instructed VP of competition, Bill Pappas, and director of aerodynamics, Tino Belli, to initiate work on the next generation of Aerokit. IndyCar presented a list of guidelines and an aggressive timeline to racecar design and manufacturing companies highlighting the main requirements of the new 'kit, inviting them to tender for the design and production elements of the job.

IndyCar had conducted tests trying different aerodynamic parts on the DW12 car. The criteria included running the cars without the rear tyre pods and experimenting with the floor to generate more ground effect. These tests intended to assess the impact on vehicle dynamics and formulate aerodynamic and engineering targets for the 2018 package.

The new Aerokit also needed to be more robust in the case of contact than previous versions, and was intended to replace all the current parts, other than the road course rear wheel pods. At this stage, minimal wheel guards were to be retained for the Superspeedway kit to satisfy stability requirements, while the underwing and road course front wing main planes could be changed to achieve the stability and performance targets.

For the Indy 500, where aero stability in a spin is critical, stability was to be at least as



IndyCar's competing manufacturers, Honda (shown in red) and Chevrolet (shown in blue), designed their own Aerokits for 2016 to fit the DW12 chassis

good as the 2016 manufacturer designs, but without the domed skid. Initially, the beam wing and beam wing anti-lift flaps were to remain for the Superspeedway races.

A performance target of 230mph was set for the Indy 500 qualifying speed, although available turbo boost could increase to achieve this target, should cornering speed be reduced too much.

A modern look

This time, the aesthetic was essential, with IndyCar stipulating a modern look to a classic IndyCar and reduced reliance on top surface aerodynamic downforce, shifting the balance to underbody-generated downforce to both increase raceability and reduce clutter, in turn, minimising potential accident debris.

The engine architecture from the DW12 was to be retained from the plenum down, allowing a new, low-slung engine cover to regain a more classic IndyCar silhouette. The turbo inlet was to be repositioned, along with the radiators in new, Coke bottle-shaped sidepods that were to include enhanced side impact structures beside the driver.

The basic premise was to strip the DW12 down to its tub, nosecone, roll hoop, engine, underwing, running gear and suspension, before then re-designing everything to fit around the bare assembly.

By November of 2016, IndyCar had made the decision to stick with long-term chassis partner, Dallara. With the tender phase of the project now complete, IndyCar could focus on the design of the new Aerokit. Dallara's in-house stylist, Andrea Guerri, had sketched several concept ideas for the original pitch, and the constructor begin to refine the concept for presentation to IndyCar.

Just prior to this, in October 2016, designer, Chris Beatty, who had worked with IndyCar on the early concept for the PPG Aeroscreen project, approached Belli about collaborating on the 2018 design. The timing was perfect as IndyCar and Dallara had reached a sticking point. The car, while ticking many of the technical and engineering boxes, had clearly been generated by an engineering team, with only a cursory nod to the design aesthetic.

This might not be an issue in some race series. After all, the saying 'form follows function' could have been written about racecar design engineers. However, IndyCar wanted to create a statement design, one that would re-establish the brand as the fastest racing series in the world.

At this point, there was still too much of the old DW12 design language on show. It was a competent racecar, designed by some of the best engineers in the world, but the car did not scream IndyCar, nor evoke the heritage and passion of the Indy 500. The car had to *look* fast, as Beatty reiterated in an early conversation with Belli: 'It needs to look like it's doing 230mph, even when it's up on the jacks.' It didn't.

Belli sent designs for the Superspeedway Aerokit to UK-based Beatty for some initial feedback. Over a weekend, Beatty sketched out a newer, faster-*looking* silhouette with swept-back wings and jet fighter-style sidepod intakes, along with several other more detailed design ideas and comments.

IndyCar fed the ideas back to Andrea Toso, project lead for the Italian firm, and over the following weeks Dallara incorporated Beatty's concepts into a new, more dynamic outline that carries through to the car we see today.

From that point on, Beatty joined the process as a consultant to IndyCar, responsible for aiding Belli in overall styling, and offering creative direction to Dallara's in-house designers and engineers.

The delay in reaching a base concept IndyCar was happy with had a knock-on effect on timelines, and the project started to fall behind schedule. From this point on, the team were flat out.

Progressive linework

The initial focus for Belli and Beatty was the Superspeedway car. Dallara further refined the aggressive look by exploring progressive angle linework. There was still a lot of polish required, with Beatty and Guerri continually finessing the lines and bouncing ideas off Belli relating to tyre ramp profiles, barge boards, rear wing end plates and other parts.

The rear wing initially used the central plain from the DW12 adorned with new low and rearward swept end plates to give it a more fluid look. The rear beam wing was also still in place, and included the rear anti-lift flaps. There were several designs drawn up around keeping the beam wing and exploring further integration with the diffuser. At this early stage, there were small winglets that protruded out across the tyre width.

'It needs to look like it's doing 230mph, even when it's up on the jacks'

Chris Beatty, consultant designer to IndyCar

Chris Beatty's 2018 rear wing included tyre ramps and a swept-back design that improved the car's aesthetic while maintaining aero efficiency. The rear wing with almost a truly swept-back end plate was not signed off, despite looking quick enough

Chevrolet's Aerokit for was tested extensively at 50 per cent before being introduced for the 2016 season

IndyCar was still not convinced about removing all rear anti-ride protection, although the winglets provided options to keep the car on the ground in the event of a 180-degree, high-speed spin.

Dallara's aerodynamicists drew up new end plates to adorn the swept-back front wing. As with all aspects of the development, the design went through a process of styling, design engineering, CFD, refinement, final detailing and wind tunnel testing, sometimes multiple times. This process ensured everything was 'on brand' with the overall car, whilst also making certain all the critical performance targets were hit.

Although the Superspeedway design was progressing well, the road and short oval version of the car was not. The body, floor and sidepods were to remain the same as the Superspeedway kit, but the low-drag wings and tyre ramps were to change for higher downforce variants.

While the aerodynamic team at Dallara went to work on the road course front wing, the stylists began to look at the rear wing. The mainplane was a widened version of the original Dallara wing but with new, smaller twin flaps. Dallara had developed several different end plate concepts, none of which were accepted, though interestingly, one of these early IndyCar concepts found its way onto Dallara's Super Formula car.

Holiday tension

It was Christmas of 2016 at this point. Dallara shut down for the holidays, but Beatty and Belli continued to work on the wings and tyre ramps over the festive period to make up lost time. To *look* fast, Beatty wanted the rear wing as low as possible. They experimented with numerous vertical and longitudinal positions and worked up countless end plate concepts. Tino's wife, artist Marina Belli, added a fresh pair of eyes at this point, helping Belli feed back on the various images Beatty was presenting, looking for that all-important 'tension' the car needed.

At last, a developed concept morphed out of these efforts that ticked both aesthetic and performance boxes. The end plate swept back from the car, giving a feeling of speed while maintaining the functional aerodynamic requirements. The rear wing concept was ready for Dallara to test in CFD when the company returned to work in the New Year.

Attention then turned to the road course tyre ramps. The Superspeedway version had not changed much from the original Andrea Guerri concept. The lines continued to gain definition as sidepod development progressed, but Guerri's original intent was still very much there, as it is today. However, Belli wanted to try something different for the road course versions. These needed to be more about downforce production, rather than high-speed streamlining. Other than that, the brief was open.

Subsequent designs varied from simple winglets and 'ski' ramps to more advanced modular systems that could function on both speedway and road courses via a removable streamline element exposing a more aggressive slope beneath it. In the end, the solution was right in front of them.

Finally, Beatty suggested utilising a modified version of Guerri's Superspeedway ramp, but with a sculpted concave top to produce the required downward pressure. 'We were chasing a design we already had,' Beatty recalls. 'The speedway ramp was such an iconic element of the oval car by now, everything else we produced just didn't look right. In the end, we used the same lower geometry but re-worked the top.'

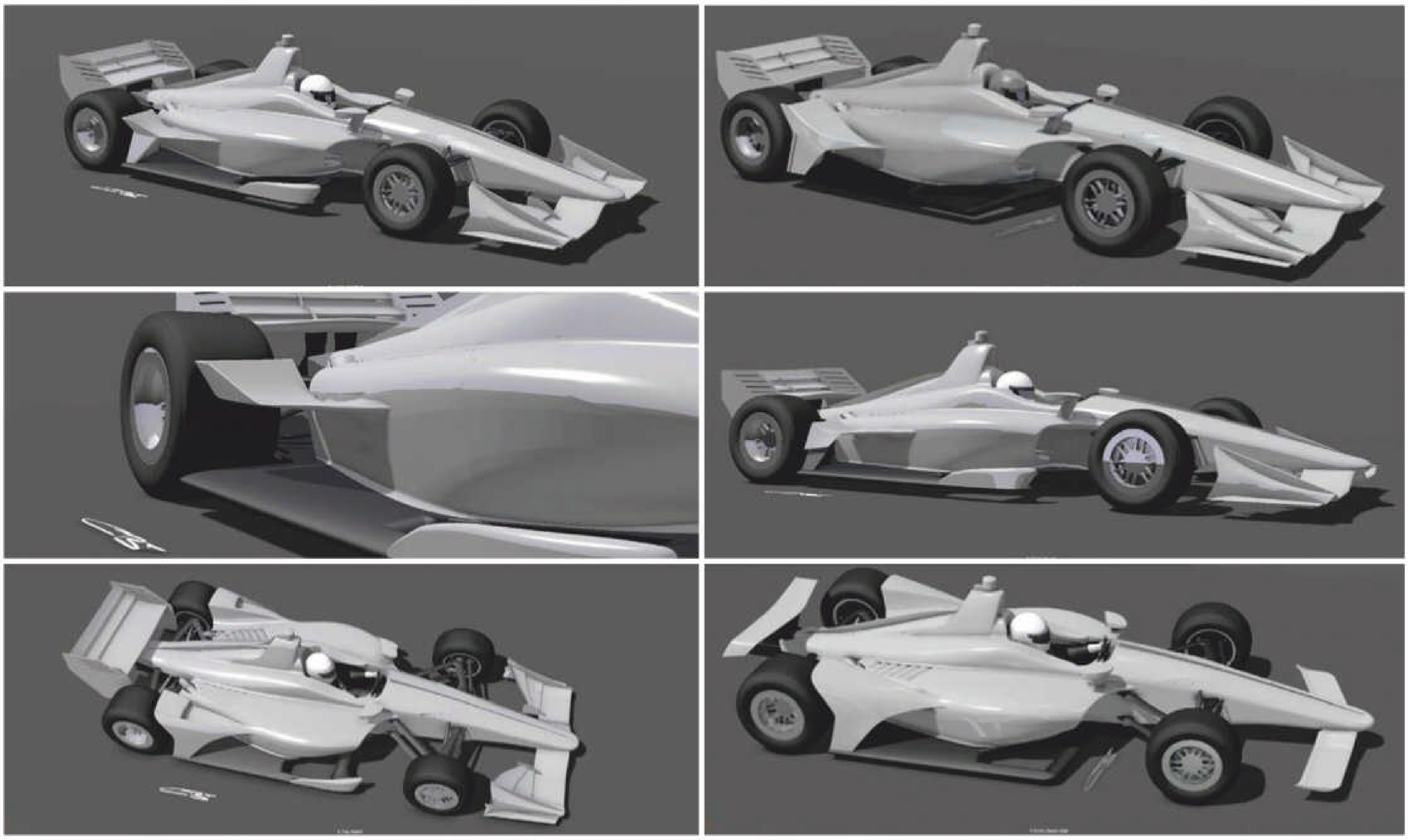
Together with the work Dallara had put in on the front wing, the team finally had what looked like a complete road and short oval concept to move forward.

Floor control

In parallel, Belli had been working with Dallara to develop the floor of the car. The intent was to reduce the dependence of top-surface downforce, instead of shifting the emphasis to floor-generated ground effect. The reason for this was to improve the downforce drop off often experienced when cars are racing close to each other.

Dallara had by now worked up the initial CAD model for the Superspeedway kit so could initiate wind tunnel testing to see how the CFD numbers stacked up with reality. With Belli in attendance, the aerodynamics department, headed up by Dialma Zinelli and Marco Milanetti, began working through how the progressed design behaved in terms of outright performance, but also compromised orientations such as a high-speed spin. Would a spinning car lift off, for example? Perhaps motorsport's biggest dread is an airborne car clearing a debris fence, and IndyCar and Dallara go to great pains to prevent this.

The new, larger sidepods had also gone through additional development. Dallara had extended the leading edge of its initial concept further forward than on the DW12 but Beatty, who came to the project via his push for greater cockpit safety and through an introduction by Stefan Wilson, wanted the leading edge extended further still.



Many different versions of the rear tyre ramp were designed in both road course and speedway trim

With the spectre of Alex Zanardi's terrible accident at Lausitz still at the forefront of his mind, the view taken was that drivers can never have enough side protection, especially with the high levels of impact frequently suffered on Superspeedways.

As a result, Belli worked with Dallara to turn the front portion of the sidepod into a full safety structure manufactured in a carbon / Dyneema fibre hybrid cloth.

Back to the future

IndyCar's president, Jay Frye, took to the stage at the Detroit Motor Show in January 2017 and gave the world its first teaser of what the future of IndyCar could look like by sharing Andrea Guerri's initial sketches with the media. Later, in a meeting with team personnel, drivers and a select group of media, Frye presented the most up-to-date renderings of the car.

It was the first real litmus test of how the car was developing, and feedback was overwhelmingly positive. IndyCar was heading back to a future that echoed its 1980's heyday. Finally, it looked like the fans, and the series, would get the car it needed to move forward to bigger and better things.

Perhaps the only 'negative' comment came from Penske's Will Power, who didn't like the road course rear wing end plate, which he felt reminded him of the now-defunct A1 Grand Prix series car. He was perhaps right. The end plate had gone through so many iterations it had become a compromise of mixed ideas.

But time was now in very short supply and, late on a Friday afternoon, Belli asked Beatty to take another swing at it, based on some pointers seen in other formulae. Within an hour, Belli, Papis and Frye received a selection of screen grabs showing the 3D outline of a new, swept back, road course end plate, featuring a horizontal reflex. A 3D turntable animation combined the wing with the rest of the car, giving the team a fuller view of the overall design, empowering them to go ahead and green light the idea.

The following week, Beatty and Belli worked the new concept up and sent a 3D file to Dallara for CFD testing. It was then a creative direction exercise between Beatty and Dallara to make sure the part also realised the aesthetic design intent. Aside from some minor aero tuning to the angle of reflex, this is the rear wing you see racing today.

With safety in mind, IndyCar debated the necessity for the rear beam wing. The beam served a purpose of providing a location for IndyCar's spin flaps – two devices that pop up when the airflow switches to a rearward bias, forcing the car into the ground and also acting as a form of air brake in the same way NASCAR's roof flaps operate.

Other than locating the flaps, the beam was not serving significant purpose from either safety or aerodynamic performance perspectives, and a cleaner back end to the car was more in keeping with the brief. With the beam removed, the safety flaps needed a new home, so Belli integrated them into

IndyCar was heading back to a future that echoed its 1980's heyday

the top surface of the rear diffuser instead, providing a tidy solution and maintaining these vital safety innovations.

The time came to reveal the car to the wider world. Autodesk, a technical partner of IndyCar, took on the role of rendering the car for both road course and Superspeedway Aerokits and the reception was again overwhelmingly positive. Fans immediately started dropping fantasy liveries onto the renderings all over social media and the media was full of praise for the new direction the series was heading in. For the design and aerodynamic teams, however, the race against the clock was still very much on.

Rear wing 'lite'

Wind tunnel testing had shown the proposed Superspeedway rear wing was generating too much drag. If the car was to reach the 230mph qualifying target at the following year's Indy 500, it needed a re-think.

Belli and Dallara now turned to the known performance of Honda's Aerokit and cannibalised a rear wing mainplane to test in the tunnel. The numbers improved, so it was decided to proceed with the new wing.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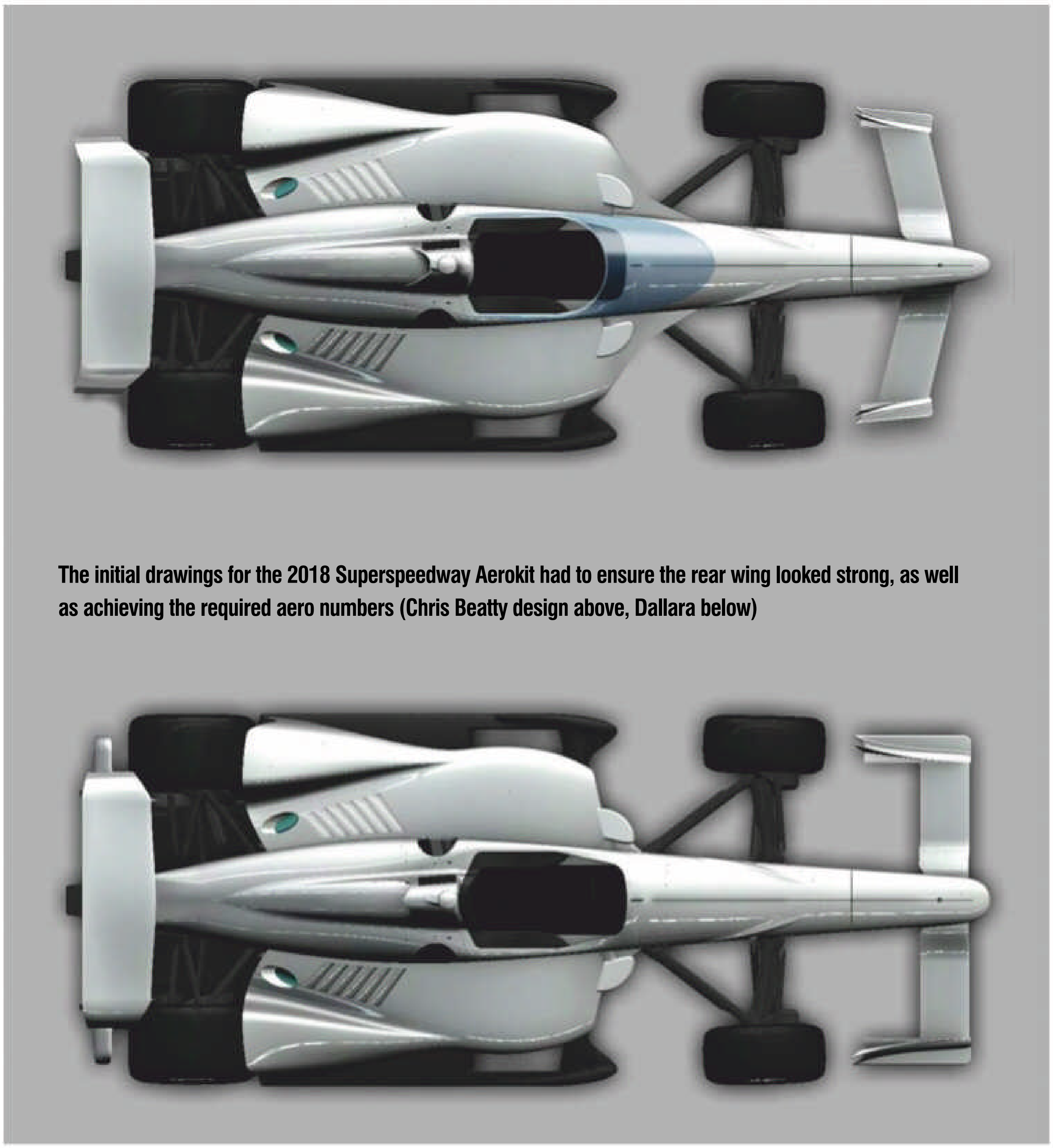
The problem was the Honda wing was very narrow, its chord, or depth front to back, was around half that of the original concept and very straight. Suddenly, the Superspeedway car went from looking visually strong to appearing weak. Not what IndyCar wanted.

Part of the issue was the Honda wing had no end plates. Devoid of its rear tyre pod-mounted winglets, it resembled a narrow plank of wood. Aerodynamically, it was on the money, but work was needed to claw back some of the aesthetic points its predecessor had scored. The challenge was on to try and make a skinny wing appear fuller. Dallara tried out traditional flat end plates, but they just exacerbated the issue. Beatty, meanwhile, pushed for the continuation of the swept back concept, with smaller end plates.

The team worked up a concept using swept-back end plates that extended rearward to give the impression of volume when viewed from the side. But these made the wing look like it had lost an element. Beatty then illustrated the mainplane with swept back edges *and* end plates. This was closer to the original aesthetic goal, but meant the Honda mainplane would need to be set aside and a new central plane developed. Dallara worked the new concept up in CFD and wind tunnel testing, and the Superspeedway car was now back looking clean and fast, even with its new 'diet' wing.



The initial drawings for the 2018 Superspeedway Aerokit had to ensure the rear wing looked strong, as well as achieving the required aero numbers (Chris Beatty design above, Dallara below)

Less is more

A further late development was the removal of the barge boards, or 'sponsor blockers' as they had become known. Sitting forward of the sidepods, these devices were intended to prevent wheels interlocking and tyre-to-tyre contact. However, with the sidepods now wider when compared to the DW12, scope for wheel intrusion was significantly reduced.

Again, to reduce potential accident debris, IndyCar made the decision to remove them entirely, which had the added benefit of further cleaning up the lines and the leading edge of the floor, as it no longer needed to support the outboard device.

There was some initial concern that the removal of the engine cover fin, tyre pods and bargeboards would reduce the amount of advertising space on the cars, making it hard for teams and drivers to raise funds, but IndyCar had Neilson calculate a 'heat map' for the new racecar. It showed that a reduction in clutter actually improved the car's overall score, the larger surfaces having more clarity. It was the age-old adage, less is more.

The development team were now down to the finishing touches, with Dallara's Guerri penning concepts for the front damper cover 'brows' that replaced the pushrod and rocker blisters. Working with Belli and Beatty, he also came up with new concepts for the mirrors that IndyCar was happy with.

Dallara then turned its attention to the manufacture of the prototype bodywork, that was to make its debut at Indianapolis Motor Speedway in the hands of Juan Pablo Montoya and Oriol Servia.

Testing was a success, with both drivers proclaiming the new configuration made the car more challenging, but fun to drive, giving driver talent the opportunity to shine. The road course set-up allowed for close running, and a car drivers were able to hustle to gain lap time and position. Raceability was back and, combined with the new, aggressive look, the drivers and fans loved it.

The car performed as anticipated in the opening races of 2018, with the road course Aerokit having an immediate effect on the quality of on-track competition. At the season-opening race at St. Petersburg, there were 110 passes between the top 10, with 11 of those becoming lead changes.

Beatty continued to work with IndyCar, Dallara and, more recently, Red Bull Advanced Technologies as the 2018 car evolved.

Following that year's Indy 500, held in abnormally high temperatures, it was apparent drivers were struggling with understeer in traffic. IndyCar and Dallara traced the issue to a small radius between the wing and end plate that was causing flow separation at certain conditions, resulting in a loss of downforce. Modifications to the wing overcame the issue for the following year, together with optional wickers and wing chord extensions for Pococono and the next year's Indy 500. *Racecar Engineering* covered this in detail in the V29N1.

Safety advances

In the run up to the 2019 Indy 500, IndyCar and Dallara introduced the Advanced Frontal Protection (AFP) pylon. Intended as a stop-gap safety device in the wake of Robert Wicken's horrendous Pocono accident, the titanium fin was designed to deflect large debris from directly in front of the driver, but IndyCar already had eyes on more comprehensive driver protection systems.

Following the failure of the self-supporting Mk1 Aeroscreen to meet the specified impact requirements, Bill Pappas and Tino Belli started to look at other options. One of which was to fit the car with an FIA-specification Halo device. Again, IndyCar drafted in Beatty to mock up what the car would look like with a Halo and carried out some initial investigation into integrating a screen with the FIA device.

The integration of the Aeroscreen with the existing chassis was challenging, but ultimately proved to be a success in 2020

The main problem was the DW12 chassis did not have sufficient reinforcing at the rear mounting points, and it would be cost-prohibitive for Dallara to modify all chassis in the series to achieve that. Therefore, Belli worked with Dallara to investigate the possibility of extending the Halo around to the DW12s original roll hoop – an area of the car that already had the required strength. The result, however, was clumsy looking, making the car look awkward and top heavy.

What IndyCar wanted was a device that combined the proven strength of the FIA Halo with the extra security offered by a screen. The answer lay in the Aeroscreen concept Red Bull F1 had put forward as a challenger to the FIA Halo, so reached out to the team to seek its assistance in developing it.

Red Bull Advanced Technologies (RBAT), headed up by Andy Damerum and Ed Collings, proceeded to develop a mechanical concept for a new form of Halo, combined with the knowledge gained from the F1 Aeroscreen project. RBAT's Mark Foster engineered the first proof of concept, which was then visualised by Beatty to give IndyCar a clear picture of the design's potential and how it would impact on the car's aesthetic.

The idea was to use a 3D-printed 'Halo'-type structure that mounted on the front bulkhead and formed a loop to the roll hoop mounting points. There were to be support pillars on either side to increase stability in a high-energy impact, which met the chassis at the driver's shoulders. A screen was to be moulded around the frame with a single curvature constant radius to reduce visual distortion to the absolute minimum. Red Bull collaborated with Dallara in finding a solution for mounting it to the existing chassis.

Cooling was also an area of development that needed further attention, with Dallara creating an intake vent under the lower leading edge of the screen.

Styling consultant

Beatty once again acted as IndyCar's styling consultant, working closely with the engineering team at Red Bull during the initial design phase of the project, included styling the overall device where engineering considerations would allow. One of these touch points was suggesting a modification to the original IR-18 damper cover, rotating it about its leading edge to form a ramp up to the top of the new Dallara screen vent. The purpose of this was to integrate the side profile of the screen into the existing angles of the chassis, reducing its perceived angle of attack and making the overall device appear less top heavy.

Beatty also added further intakes, cut into the new cover to feed the venting system to tie in with the existing car styling. Dallara then developed these designs through CFD aero testing to ensure sufficient airflow actually reached the drivers in practice.

The rear fairing and the form of the screen's 'blacking' were all areas the screen could be worked on to make the car *look* fast, and Beatty developed a number of concepts with Belli and Pappas to help Red Bull develop a device that would fit with the design attitude of the car.

The one area where they were limited was the screen's frontal profile, mainly due to the original vertical sides of the tub. The screen's top access needed to be the same size as the original cockpit opening to allow emergency crews to interact with an injured driver unimpeded. It was also driven by what Red Bull call the 'helmet box', an invisible area around the driver's helmet that represents possible head movement in a crash. The idea was that no part of the screen's structure could encroach on this volume to make sure the device itself couldn't inflict an impact injury on the driver.

Red Bull's Aeroscreen was introduced to the world by Jay Frye and Christian Horner at the 2019 Indy 500 Carb Day. In the background, Belli and the teams at Red Bull and Dallara had moved on to prototyping the screen, testing it with driver, Scott Dixon, in the Dallara simulator. Other partner companies also came on board to add material and manufacturing expertise to the project with the frame manufactured in 3D-printed titanium by Pankl – a magnificent piece of engineering, incidentally, that Frye described as 'a work of art.'

Competition debut

As Covid-19 delayed the start to the 2020 racing season, the first race at Texas Motor Speedway saw the screen make its competition debut. Its first real on-track test, however, came at Iowa when Colton Herta's car climbed over the cockpit of Rinus VeeKay, almost immediately proving its worth as a potential lifesaver.

The Aeroscreen has been a critical addition to the plethora of safety measures already developed by Dallara and IndyCar. It is also an incredible innovation for the racing industry as a whole, and IndyCar prides itself on never standing still when it comes to looking after the safety of drivers and fans.

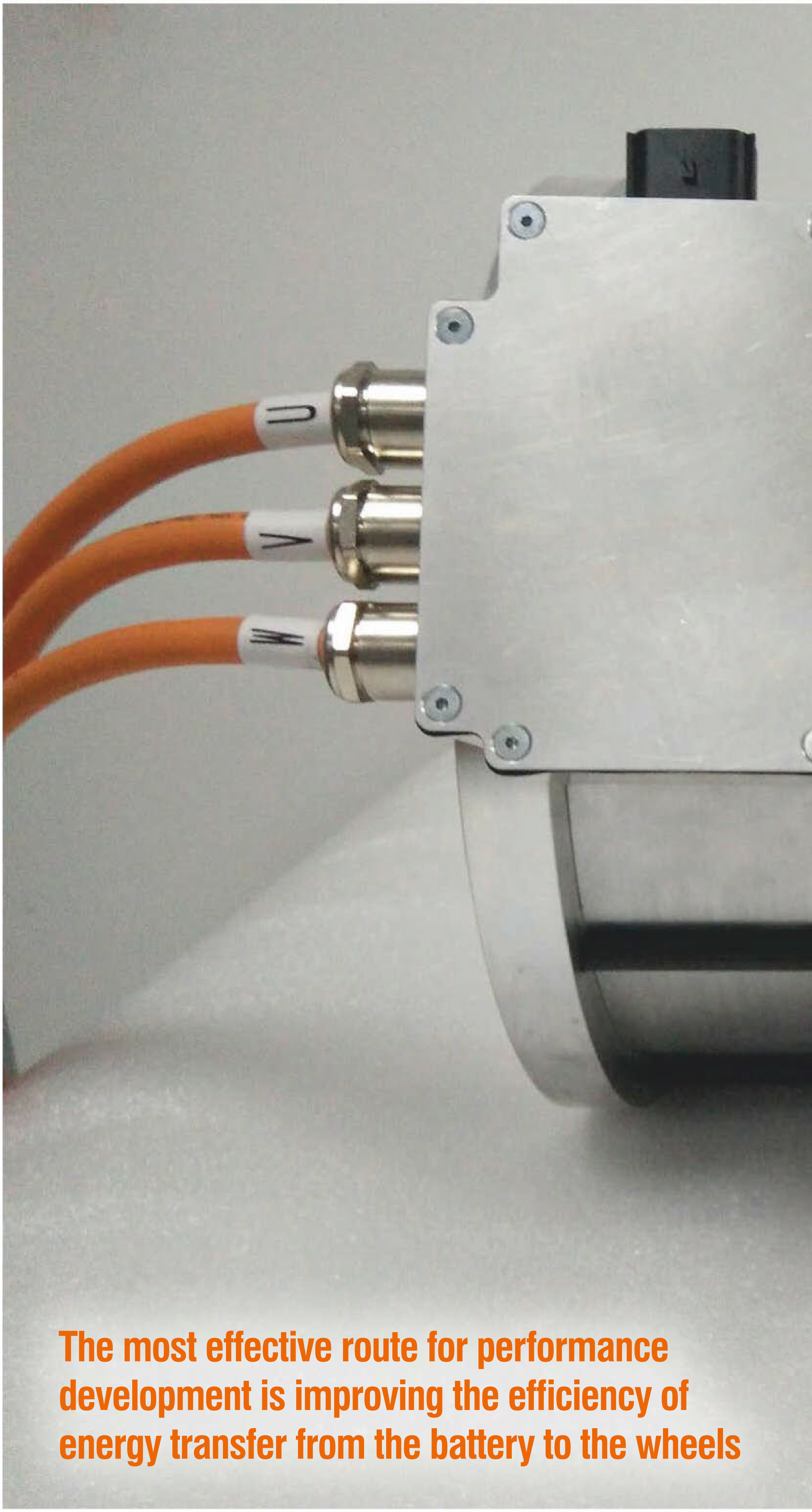
As for what is to come for the series in terms of a next-generation car? Well, with Covid-19 continuing to cause havoc across the globe, and the recent acquisition by Penske, all we currently know for certain is there are new engine regulations coming in, and it's going to be fast!

The road course set-up allowed for close running, and a car drivers were able to hustle to gain lap time and position.

State of flux

Racecar investigates the differences between the axial flux and radial flux motors currently used in motor racing

By LAWRENCE BUTCHER



The most effective route for performance development is improving the efficiency of energy transfer from the battery to the wheels

Electrified motorsport is here to stay, whether one is talking hybrids in Formula 1, the World Endurance Championship (and soon the World Rally Championship) or pure electric, pioneered by Formula E. This will soon be joined by series such as Extreme E, electric Touring Cars and Rallycross.

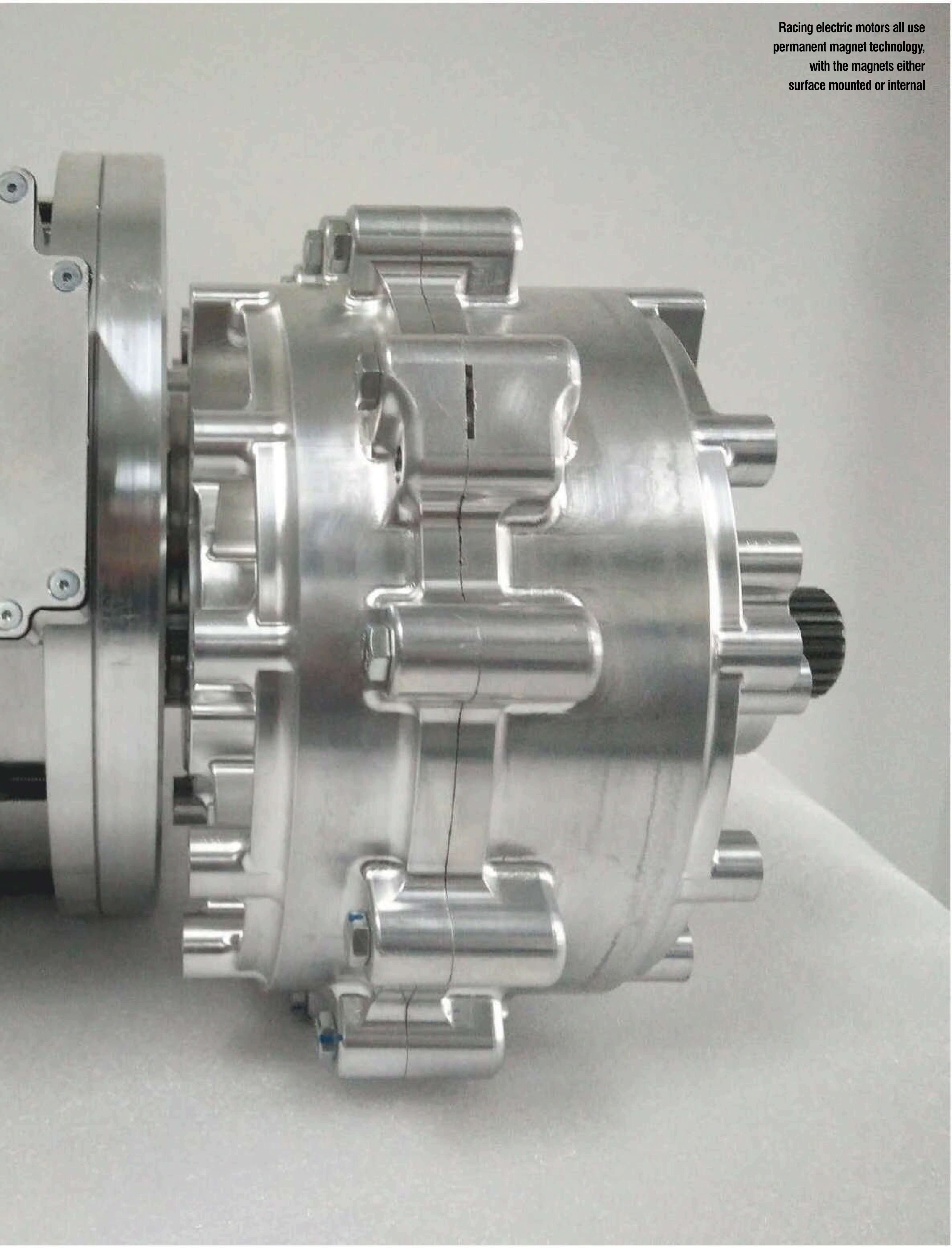
However, much like traditional internal combustion (IC) racing, there is no such thing as a standard architecture for electric motors, and in this article we will take a look at the two main topologies, axial flux and radial flux, exploring how and why they are different and their various pros and cons.

All rotating electric motors share two common components, a rotor and a stator. The stator is fixed and the rotor, as its name suggests, rotates. Commonly, the rotor sits inside the stator, though there are also external rotor motors, such as those found on some in-wheel applications.

Permanent magnets

For the purposes of racing, it is only worth considering permanent magnet machines, so induction motors will be left for production cars. In a permanent magnet motor, the rotor is constructed from permanent magnets, and these can be either surface mounted or internal. Surface mounting is more efficient, but creates a more complex problem when it comes to securing them at high rpm.

Racing electric motors all use permanent magnet technology, with the magnets either surface mounted or internal



The principle of operation is based on the interaction between the rotating magnetic field of the stator (made up of multiple coils, which are energised) and the constant magnetic field of the rotor. According to Ampere's law, this interaction creates a torque reaction, causing the motor to rotate. The speed of the motor is controlled by changing the magnetic field of the stator and, in the case of traction motors, via a variable frequency drive.

The differentiation between axial and radial flux motors relates to the flow of the magnetic fields, or flux. In a radial flux machine, the flux runs radially in relation to the rotational axis of the machine, while in the case of an axial flux design it runs parallel to the rotational axis. Until relatively recently, radial flux machines dominated but, over the past two decades, a number of manufacturers have developed axial flux technology on a commercial scale.

Figure 1 shows a simplified schematic of both axial and radial flux topologies.

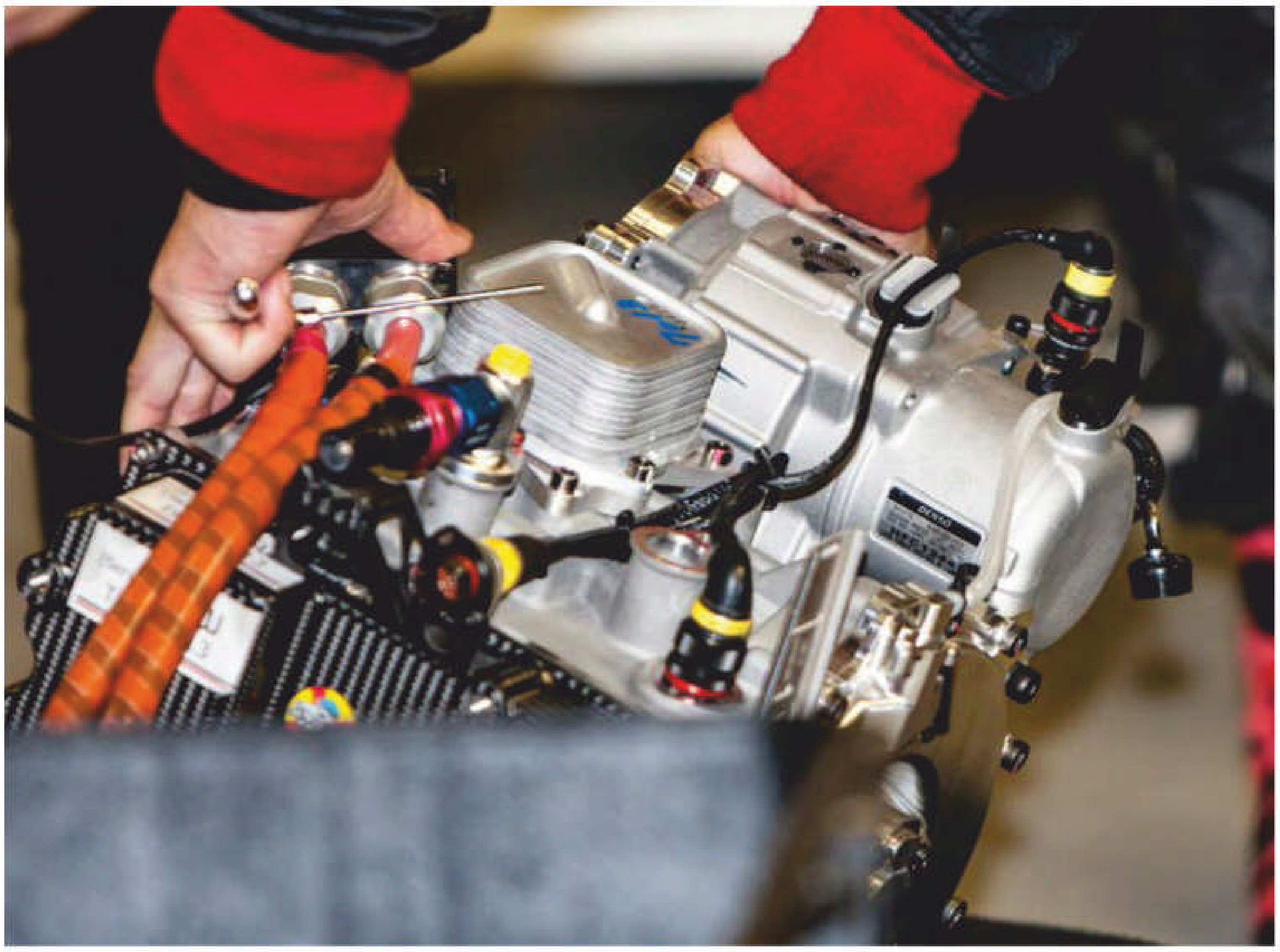
In terms of construction, radial flux motors tend to have a length greater than their diameter, while the opposite is true of axial flux motors, hence why they are often referred to as 'pancake' motors. This layout gives the axial arrangement an inherent mechanical advantage, as the magnets on the rotor are located further from their axis of rotation, thus create a greater torque effect.

The reason radial flux motors were dominant for many years is due to the manufacturing and electrical design challenges that must be overcome to create an axial flux machine. For example, due to the layout of the stator and rotor, and the magnetic forces involved, ensuring that a consistent air gap is maintained between the two requires a strong structural design. Furthermore, cooling of the motor windings, in an axial motor where the rotor is located external to the stator, can be challenging. For this reason, some designs (such as the layout illustrated in **Figure 1**) have placed the rotor centrally to negate this issue.

Manufacturing process

Additionally, unlike in a radial flux machine, where the stator is made up of a stack of electrical steel laminates, the stator in an axial flux machine, while still made from laminates, takes the form of a spiral. This requires a very different manufacturing process where a band of steel is wound into a spiral while simultaneously having slots stamped in it.

This manufacturing method is one of the reasons axial flux machines are complex to produce, perfect alignment of the slots in each laminate layer being vital to ensuring maximum performance. An uneven surface along a slot will reduce the efficiency of heat transfer from the stator core to the windings.



Toyota deployed a radial flux motor in its Le Mans-winning TS050 Le Mans Prototype

As the laminate layers are formed into a spiral to create a core, too great a tolerance in the dimensions of each discrete slot in a laminate layer will lead to a 'wavy' surface.

Performance of each motor type is increased using similar methods – ensuring a reduction in both mechanical and electrical losses, increasing the potency of the magnetic materials used and tightening tolerances such as the air gap between the rotor and stator.

For magnetic materials, the favoured choice is neodymium (NdFeB), a rare earth magnet and one of the strongest commercially available magnetic materials. One of the key limitations of this material, though, is a relatively low resistance to temperature. Above around 80degC it begins to lose performance, though different grades are available that can withstand higher temperatures. This demand places a significant requirement on the cooling design of a motor, specifically the rotor. Buried within the stator (at least in the case of a radial flux machine) this can be challenging, but several manufacturers have developed rotor cooling systems that negate these issues.

Another solution is to use magnets made from materials such as samarium cobalt, which has a much higher temperature resistance, but is less magnetically potent. For example, in the case of the two MGUs fitted to the Porsche 919 LMP1, the German manufacturer opted for samarium magnets in its exhaust-mounted MGU because of the extreme temperatures, and for the front unit to ensure reliability. Though the motor would normally operate within the range of neodymium materials, if there were to be an issue with the cooling system – and given the role of the car as an endurance racer – it wanted the ability to run for extended periods at elevated temperatures.

Material performance

The stator material also plays an important role in performance, with both the type of material and thickness of the laminates coming into play. This applies across both axial and radial flux motors. In high-performance applications, cobalt steel is one of the favoured materials. The role of the material is to facilitate the flow of the magnetic flux, and with a higher magnetic saturation point than standard electrical steels, the use of cobalt steel both reduces losses and increases torque density.

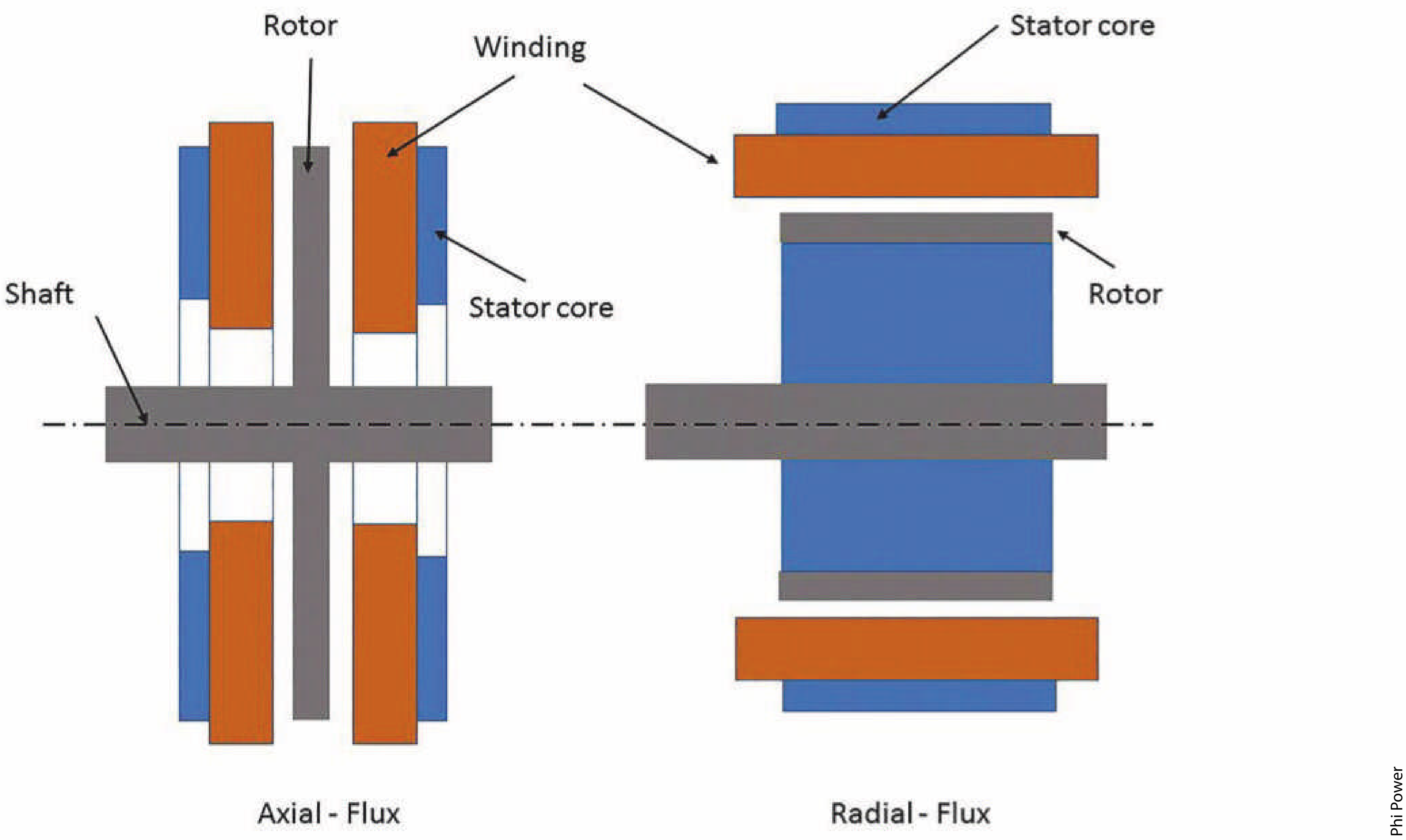
The thickness of the laminates also has a role to play in the efficiency of the motor. The thinner the laminates, the lower the losses. Currently, the thinnest commonly available are 0.1mm, but the manufacturing process of very thin laminates is complex and consequently they are expensive.

There are of course a host of other factors that dictate performance, such as the fill factor of the stator windings (how much wire can be crammed into the slots), as well as regular mechanical considerations, including frictional losses and weight reduction.

Pros and cons

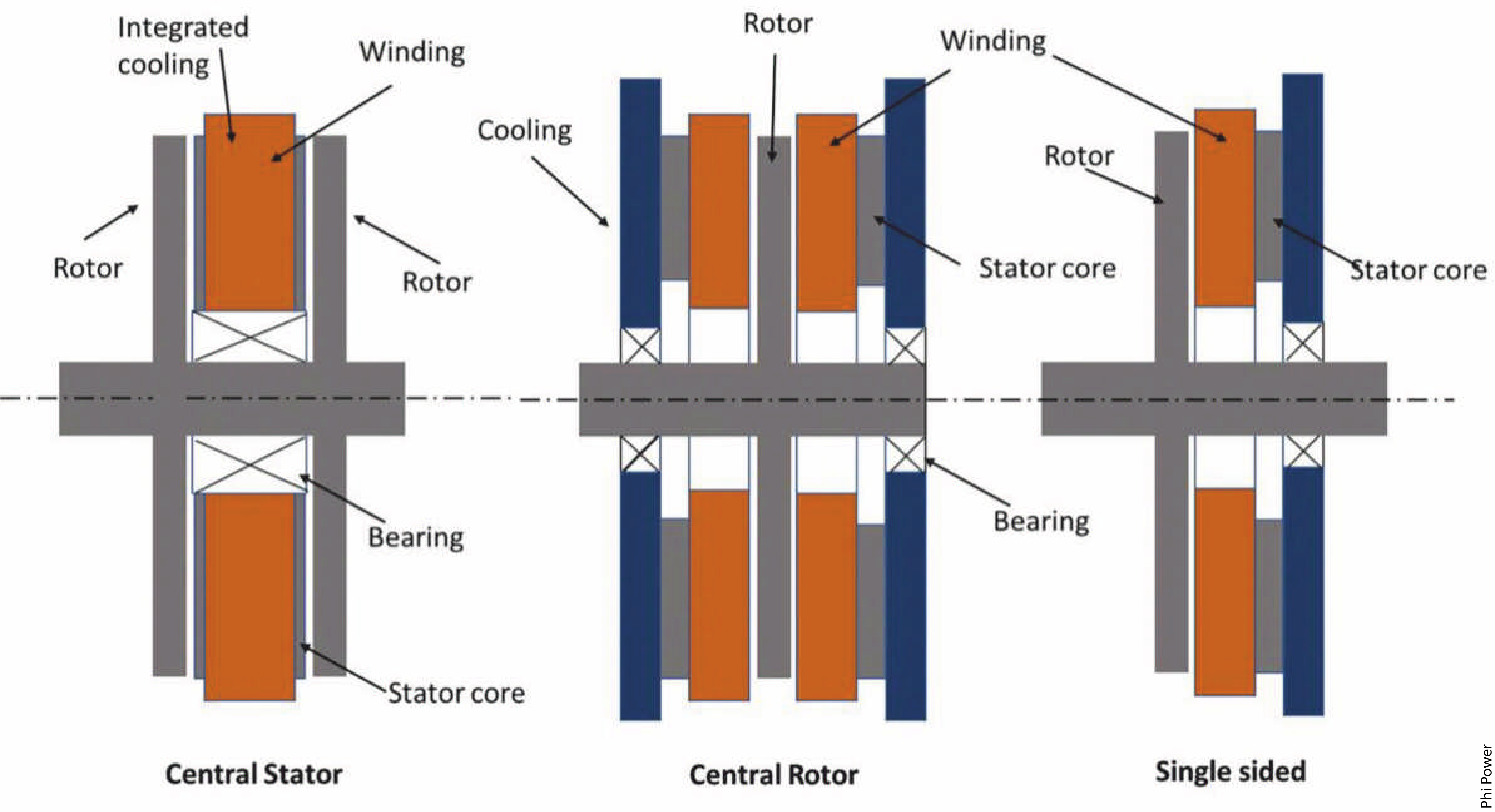
If one looks across all the current motorsport applications, one finds both axial and radial flux motors in use. There are benefits and disadvantages to each type that relate to their maximum power and torque potential, weight and packaging requirements.

Figure 1: Simplified schematic of axial and radial flux motor designs



Phi Power

In terms of construction, radial flux motors tend to have a length greater than their diameter, while the opposite is true of axial flux motors



Phi Power

Figure 2: Types of axial flux motor

Audi's new MGU05 comprises a six-phase SPM radial flux motor capable of 'in excess of 20,000rpm'. With its composite stator housing, the 250kW unit weighs just 35kg

Record setter

Earlier in 2020, US drag racer, Steve Huff, became the first to crack the 200mph barrier over the quarter mile in his Current Technology electric dragster.

Huff's ET of 7.520 seconds at 201.07mph is an impressive feat given his nearest competition was Don Garlits and his Swamp Rat 38 dragster. To achieve the record-setting run, Huff's car harnessed a pair of axial flux motors supplied by Swiss company Phi Power, giving a combined torque of 2400Nm and a power output of 1.6MW.

The motors were dual core units, meaning each housing contained a pair of rotors stacked in line with each other. Running at 800V, the motors were controlled by four Rinehart controllers, rated at 700A, fed by a lithium polymer battery pack. With the motors running to a peak of 8000rpm, power was transferred to the track via a three-speed transmission from Owens.

The achievement of Huff and his car highlights the benefits axial flux motors can bring in the right applications, in this case, providing a formidable power output in a very compact package.

Taking the example of Formula E, it would appear the entire grid is now using radial flux motors. However, up to quite recently, several teams, including Mahindra in 2020 (with a ZF-supplied unit), utilised axial flux units, so why the change?

One word; regulations. While development of the motors, power electronics and transmission are relatively open, the battery is a spec part with a fixed energy capacity and system output. This means the most effective route for performance development is improving the efficiency of energy transfer from the battery to the wheels.

Nevertheless, the gains to be found are relatively small. Even in the first season of competition the spec McLaren drivetrain, which featured a pretty inefficient transmission, was over 90 per cent efficient.

For a given size and weight, an axial flux motor will normally have a higher torque density than a radial flux unit

This means even small gains, which allow teams to eek a little more out of the capped battery power, can be decisive.

Torque density

For a given size and weight, an axial flux motor will normally have a higher torque density than a radial flux unit, and the potential for compact packaging is one of the reasons axial flux motors tend to be favoured in applications such as motorcycles, where there is little width available to mount a motor. In such a situation, a longitudinally-mounted radial flux motor would increase the complexity of transferring drive to the rear wheels. Similarly, if one looks at Formula E, several manufacturers deployed axial flux motors as the layout allowed for two to be stacked next to each other across the width of the transmission / chassis.

However, the benefits of an axial flux motor relative to a radial flux one only apply at relatively low rpm. As rpm increases, the mechanical design of an axial flux motor begins to work against it. Theoretically, an axial flux machine can be spun at high speeds, but the physical challenges of doing so are considerable. With a radial flux machine, you can keep the diameter small and, if you want more power, you just make it longer.

Friction losses and structural forces relate to the diameter of the rotor. With an axial machine, to increase power you increase the diameter, but then you start to run into problems with friction and structural integrity at high speeds (though on this last point, the development of new materials such as aluminium metal composites have shown promise in such applications).

As powertrain suppliers in Formula E have used very advanced motor designs to push rpms higher, in pursuit of power rather than torque, the balance has tipped in favour of radial flux machines. Therefore, the constraints of the rules and, importantly, the budgets available to support the technology development needed, favours the use of a very high speed, radial flux motor coupled with a lightweight transmission.

For example, looking at the recently released images of Audi's MGU05, fitted to its season seven car, it comprises a six-phase, SPM radial flux motor with a composite housing around the stator. Every element of the motor is optimised in pursuit of efficiency, running 'in excess of' 20,000rpm, which means likely nearer 30,000rpm given the current state of play. Audi says it realised an efficiency of over 97 per cent across all running conditions, with an all up weight for the 250kW unit (including inverter) of 35kg.

When it comes to using every joule of energy in the most efficient way possible, a very high rpm radial flux motor appears to present a more efficient overall package than an axial flux motor. The difference is not huge but, with such fine margins, it is significant.

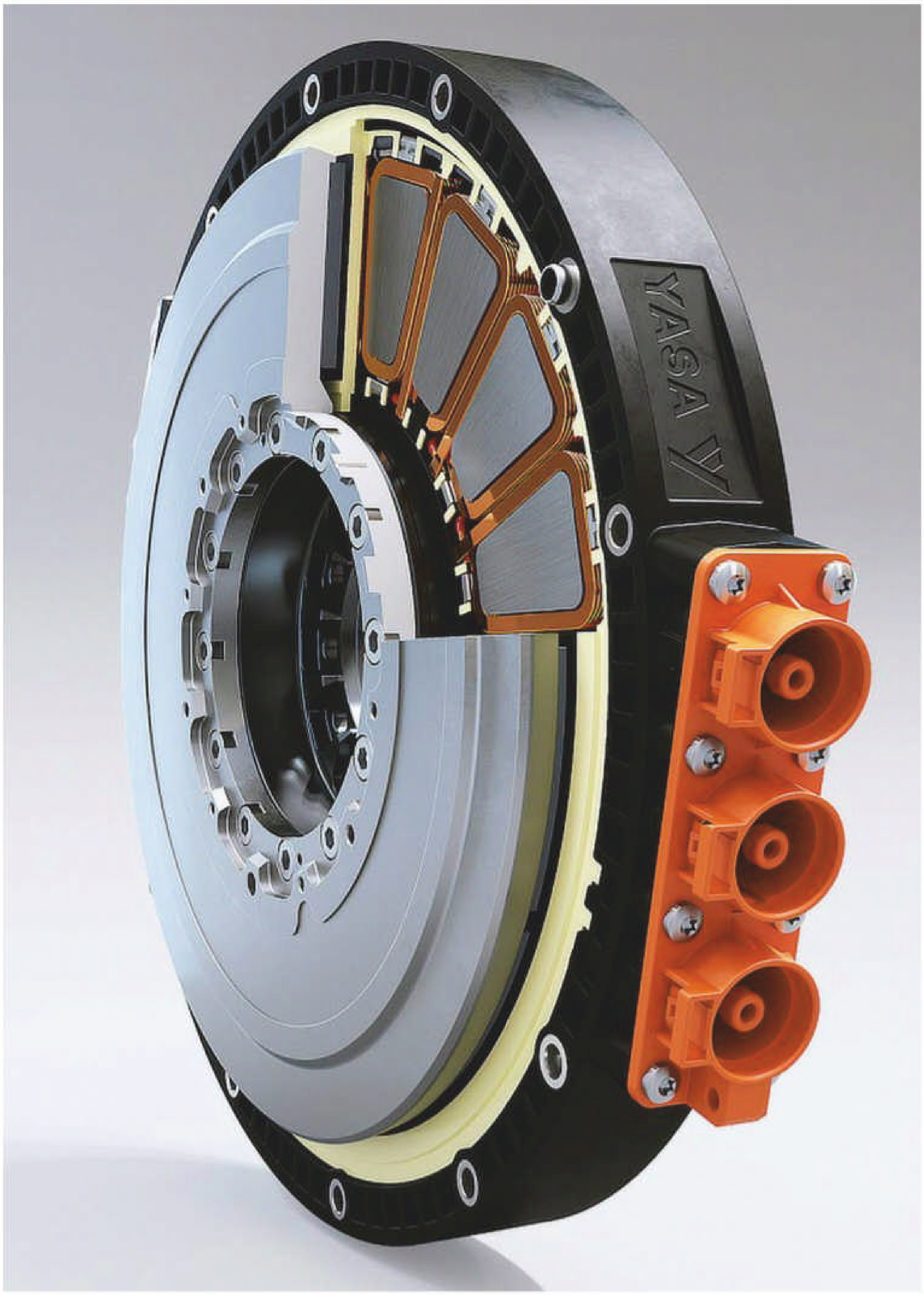
The case for axial flux

This does not mean there is no place for axial flux machines in racing. If extracting every ounce of power from a battery system and a 30,000rpm motor is not required, an axial flux machine will provide a better power density than radial flux, at more reasonable cost.

Take, for example, the YASA motor design as used in the (former) Virgin Formula E car, as well as applications such as the Drive eO PP03 that was the first electric car to win Pikes Peak in 2015. YASA stands for Yokeless And Segmented Armature, which describes the motor's topology. Essentially, the YASA motor is a type of axial flux motor that has no stator yoke, a high fill factor (the density of the windings) and short end windings that all work together to increase the machine's torque density and efficiency.

This topology is based around a series of magnetically separated segments that form the stator of the machine. The result is a very impressive specific output, which is the result of a combination of improvements in the magnetics, cooling and packaging of the motor compared to other designs.

Key amongst these improvements are the significant weight savings achieved by eliminating unnecessary magnetic material from the stator, coupled with a design that uses considerably less permanent magnet material in the rotor. Another important factor is the flexibility of design afforded by the use of powered iron for the magnetic components, allowing for highly complex shapes to be manufactured easily.



YASA (Yokeless And Segmented Armature) is a compact, lightweight, powerful type of axial flux motor with no stator yoke

Size zero

There are various other layouts of axial flux machine available beyond that used by YASA. For example, Swiss supplier Phi Power, which provides motors for applications ranging from industrial equipment to motorsport, features a pair of stators that sandwich the rotor.

Other variations on the axial flux theme include the designs produced by UK-based Saietta. Though the company is currently focusing on the production of small, cost-effective motors, rather than outright power units more suited to automotive motorsport applications, it was until recently involved in the production of high-performance motors that were used in a TT-Zero motorcycle. Saietta's motor designs are of the axial flux type, but differ from others on the market as they combine the benefits of both a yoked stator AFM using distributed windings and a yokeless stator AFM with concentrated windings. This can be best described as a yokeless stator with a distributed winding.

Each manufacturer will obviously claim its solution is the best, but currently there are a number of ongoing e-Motorsport projects harnessing axial flux motors of differing designs. For example, the Pure ETCR series will use a spec electric powertrain supplied by axial flux specialist MAGLEC, with a twin motor set up producing 500kW. Meanwhile, Ford's Mustang Mach-E 1400, though not strictly a racing vehicle, uses no less than seven YASA 400 motors.

While radial flux units are certainly more commonplace, there will doubtless be further applications for axial flux technology as electric racing becomes ever more widespread in the coming years.

When it comes to using every joule of energy in the most efficient way possible, a very high rpm radial flux motor appears to present a more efficient overall package than an axial flux motor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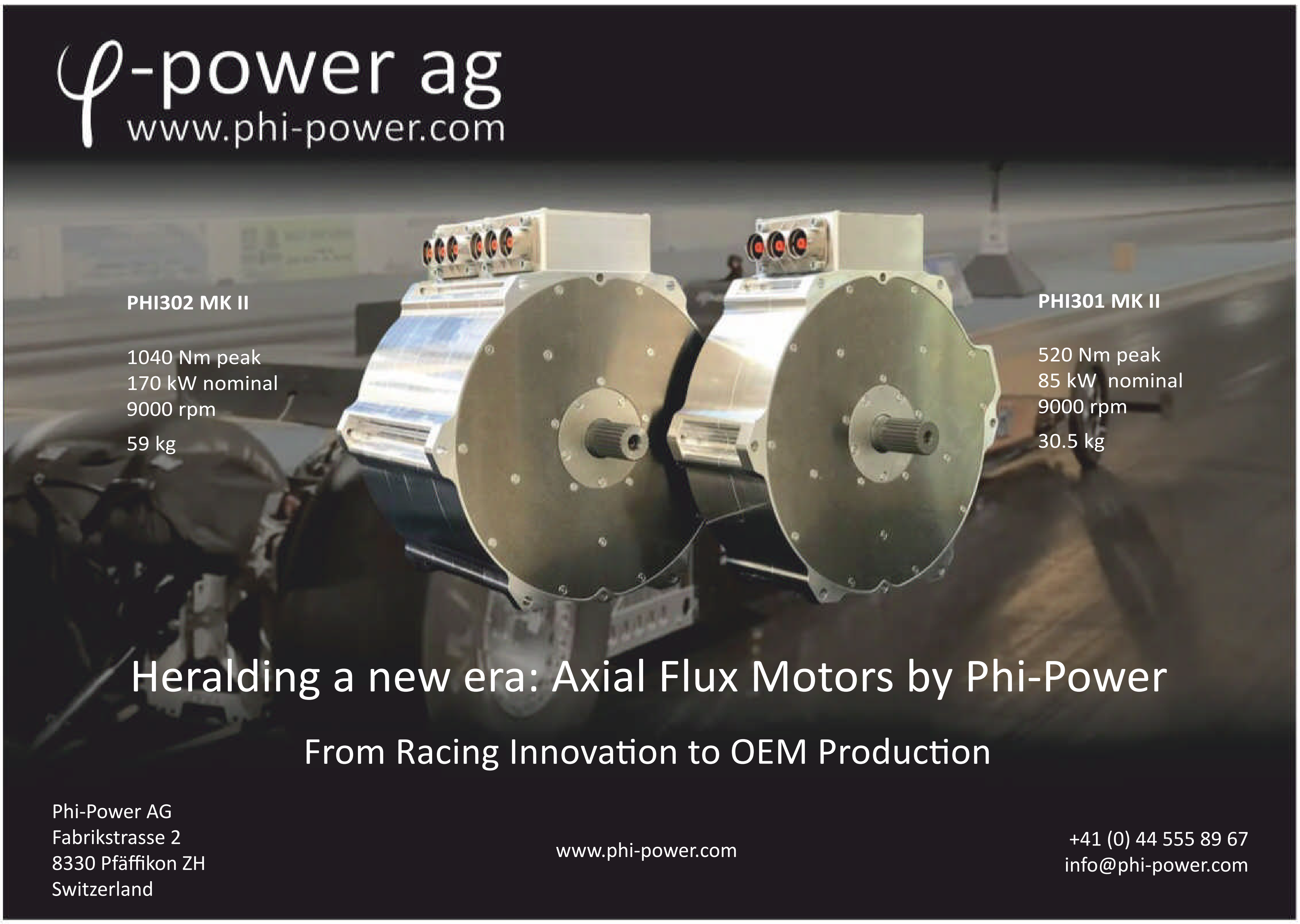
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Current thinking

We need to talk about electric powertrains. Again

By DANNY NOWLAN

In *REV*29N7, I wrote an article exploring the current state of play of electric powertrains. That was over 18 months ago now, though, and quite a bit of water has flowed under the bridge since then. Both BMW and Audi have recently pulled out of Formula E, no doubt due to European governments constantly talking about banning sales of internal combustion motors post 2030. Consequently, re-visiting this topic is now more important than ever.

In recent times it has become virtually impossible to have a rational discussion about this because the subject of electric powertrains in motorsport and automotive applications has become polarising. I can honestly say I've never seen a subject promote such extreme reactions. On one hand you have Utopian optimists who contend that battery-powered electric propulsion will eat internal combustion engines alive. Then you have the those who contend that electric propulsion is nothing more than a false dawn. On top of that, you have the likes of Greta Thunberg *et al* who will latch on to a solution and stick with it with religious zeal, regardless of the consequences, and woe betide any who play devil's advocate.

Informed decisions

The purpose of this article is to assess the current state of play with electric powertrains. I'll present the good, the bad and the ugly. Given how divisive this issue is, my goal is just to present the facts so you can make informed decisions. Unfortunately, this pragmatic approach has been sadly absent in much of the recent discussion about electric vehicles. It's also time for an engineering grown up to turn up to this discussion.

Before I begin, it might be wise to lay my cards on the table. I've written before on a number of occasions on electric powertrains, laying out the basics and then exploring their use in categories such as GT3 and Time Attack. Where this comes from is the development of the ChassisSim Electric Powertrain module. This has been used in Formula E and some other projects coming down the pipe that I have to remain tight lipped on.

In addition to this, for the last 25 years, day in day out, I have been flying high-performance, electric-powered pylon racers and extreme aerobatic aircraft. I started off with NiCad / brushed motor-powered gliders that could barely cope with 20km/h winds and now fly LiPo, brushless-powered monsters that will blast into winds of 40km/h with complete abandon and hit 160-260km/h with no problem. To underscore the advancements of electric propulsion I've never felt the need to fly internal combustion motors.

So it's fair to say I have some skin in the game, as it were.

To understand the current state of play, we need to understand why electric vehicles have received the phenomenal amount of press that they have. When you started to get a Tesla Model S that could go 400km on a charge and blow away Porsches on the standing quarter mile, a lot of de-skilled politicians and senior bureaucrats figured it was the dawning of the new Age of Aquarius. However, as always, the devil is in the detail.

The reason an electric road car can do 400km is because the way engine torque is used in that application is fundamentally different to in motorsport. In racing, drivers spend 60-70 per cent of the time on full throttle. In an aerospace application, that figure rises to 70-80 per cent of maximum engine torque all the time. For road car use, you are lucky if you go beyond 10 per cent throttle.

Figure 1 is an analysis I did for one of my re-sellers, Altair Engineering, about using the ChassisSim Electric Powertrain module for road car use.

This was a typical usage pattern I came up with for mixed city / highway driving, with a cruise throttle of 10 per cent and the occasional stab to 20 per cent when you want to be naughty. I simulated a 10km drive pattern, and you can see the Ah usage of the battery pack was 4.3Ah. So, given the pack voltage was 700V, this is about 3kWh for this example.

With this usage, a Tesla Model S with a battery pack of 85kWh will get about 270km range. Given I have been a bit generous with throttle, this is the reason a Tesla Model S can achieve a range of 400-500km. However, the major reason it can do this is because you can be gentle with the throttle. You don't have this luxury with motorsport or aerospace applications.

Left for dead

Another reason electric vehicles have garnered so much publicity is in drag races where you see a Tesla Model S leaving a high-performance muscle car for dead. The reason for this is simply the torque delivery of an electric motor vs an internal combustion motor. With the latter, particularly a high torque one, you are doing handstands if you can hit 10,000rpm.

One of the Holy Grails of internal combustion motor tuning is achieving a flat torque vs rpm curve. Electric engines, on the other hand, have a flat torque curve that responds instantly and, in a lot of cases, can turn at up to 20,000rpm. Hence why a Tesla Model S configured in insane mode will beat its equivalent spec internal combustion motor counterpart in a drag race every time.

This neatly segues into one of the big advantages of electric powertrains, and that is responsiveness. Talk to anyone who has tuned an internal combustion engine and they'll tell you they spend most of their time trying to get the torque vs rpm curve as wide as possible. And a lot of time tuning throttle response.

With electric motors, the only thing you are playing with is the timing on the brushless motors (in other words, the angle between the rotor and the magnets) and the PWM (pulse width modulation) frequency. Most electric speed controls will have a perfectly linear response, so it's effectively an afterthought.

To underscore the advancements of electric propulsion, I've never felt the need to fly internal combustion motors

In racing, we spend 60-70 per cent of our time on full throttle. For road car use, you are lucky if you go beyond 10 per cent throttle

A case in point is RC 3D aerobatic aircraft powered by an internal combustion motor, where you are always chasing the throttle response map. In the electric community, we set the motor timing and range check the throttle when we first install the electronic speed control. After that, you never touch it.

Advantage packaging

A further advantage of electric powertrains is motor packaging. A really good example is the Remy HVH 250 motor. The higher end applications can punch out 250kW, weighs in at 57kg and can be packaged in a space 300 x 200 x 200mm. This is inconceivable for an internal combustion motor, and offers a plethora of opportunities designers and engineers simply don't have with an IC motor, such as electric motors fitted to all four axles, for example. This handles the nightmare of the differential quite elegantly.

And then there's maintenance, or lack thereof. Internal combustion motors are notorious for their maintenance requirements. Try running a modern road car well past its 10,000km service interval and see what happens. This is even more pertinent with a race or aerospace engine.

In contrast, if you run an electric engine within its voltage, current, load and temperature limits, they last forever. This is one of the primary reason OEMs have been so spooked by electric vehicles because where car manufacturers make a significant part of their money is finance schemes and replacement parts. Electric engines mean the latter part of that equation falls apart. That said, there is a flip side to this but we'll discuss that shortly.

Where electric engines shine, particularly in motorsport use, is in sprint events. It is no accident Volkswagen was able to smash the Pikes Peak record with its electric ID. R. Also recall I did an analysis on an electric-powered Time Attack Lotus Elise for the Open category World Time Attack Challenge held at Eastern Creek raceway in Australia every October. With the like-for-like replacement, the results shown in **Table 1** were found.

Further studies found that when the electric car was reduced to 930kg, there was little difference between the internal combustion and electric engine equivalent.

Electrics could shine in club motorsport sprint events, too. In such formulae, cost is always a premium, and the lack of engine maintenance for an electric-powered contender could be quite enticing. Provided you have the capability to charge the vehicle, of course.

Which is why electric engines come into their own for short range, urban road car use. If we refer back to **Figure 1**, in a road car application you are in the range of 0-20 per cent throttle. One of the worst things you can do with an internal combustion engine is to turn it on and off all the time. And if you want to make it last, you have to warm it up properly before use. An electric engine has no such drawbacks so, if your operating radius is 100-200km and you are fortunate to always be able to park in front of a charging point, electric vehicles offer a genuine and enticing alternative.

Indeed, I would contend for lots of reason the real blind spot in OEM automotive is the small cargo urban class car. Think Toyota Yaris, or similar. This is where battery-powered EVs offer a fantastic, ready-to-go solution but, once again, there is a flip side, which we will come to shortly.

Power struggle

Where an electric powertrain struggles is when you need persistence. One of the things that has largely been left unsaid in so much recent discussion on the subject is the old favourite question – what can fit into a tea cup and take you a kilometre? Petroleum, of course! This is one of the most significant challenges to going carbon neutral, particularly when it comes to transport.

Table 1: Lap time analysis ICE vs electric for Lotus Elise Open class World Time Attack challenger at Eastern Creek

Item	Lap time (s)
Internal combustion	84.72s
Electric	85.9s

Figure 1: Typical road car use of an electric powertrain

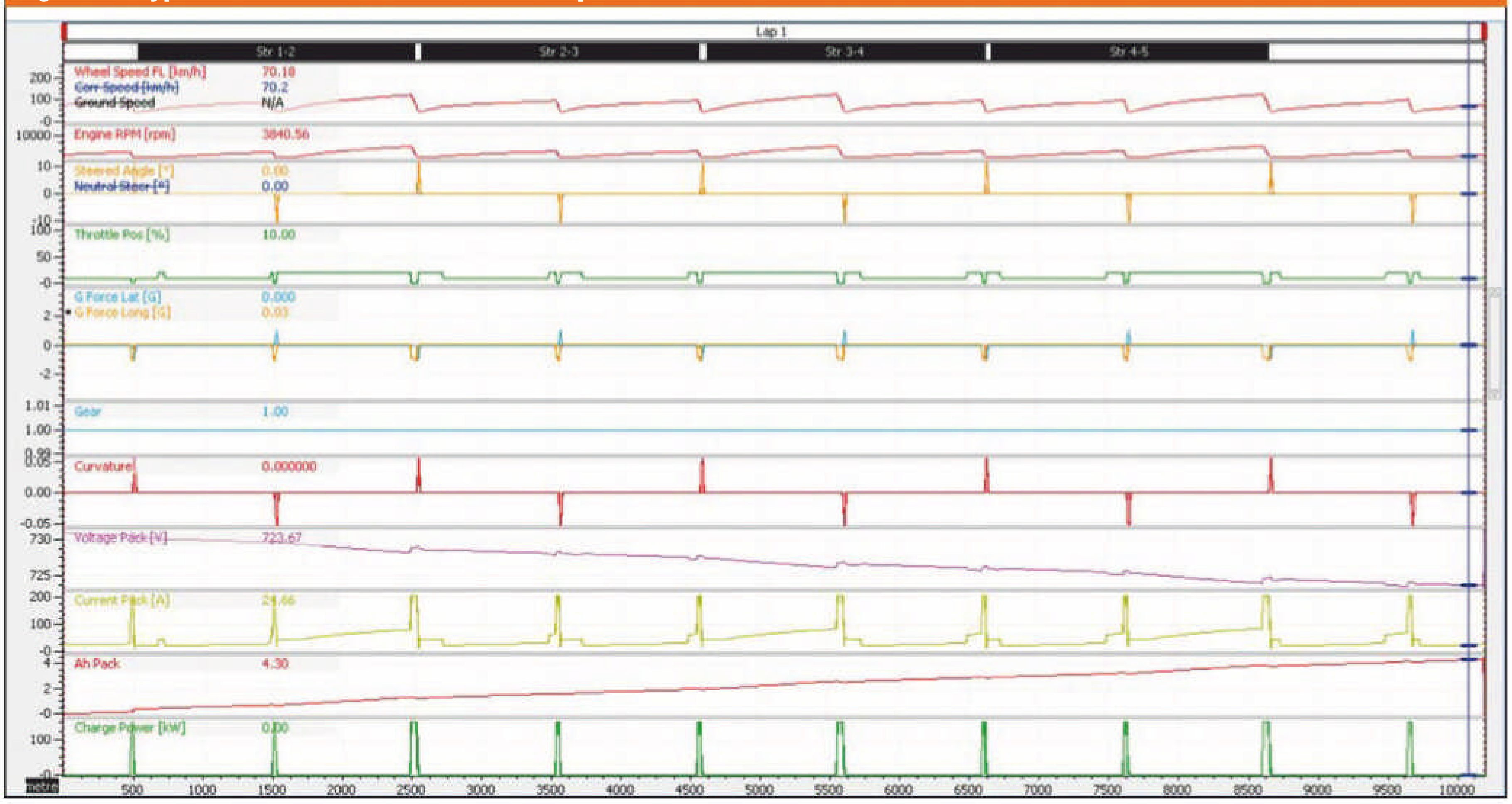
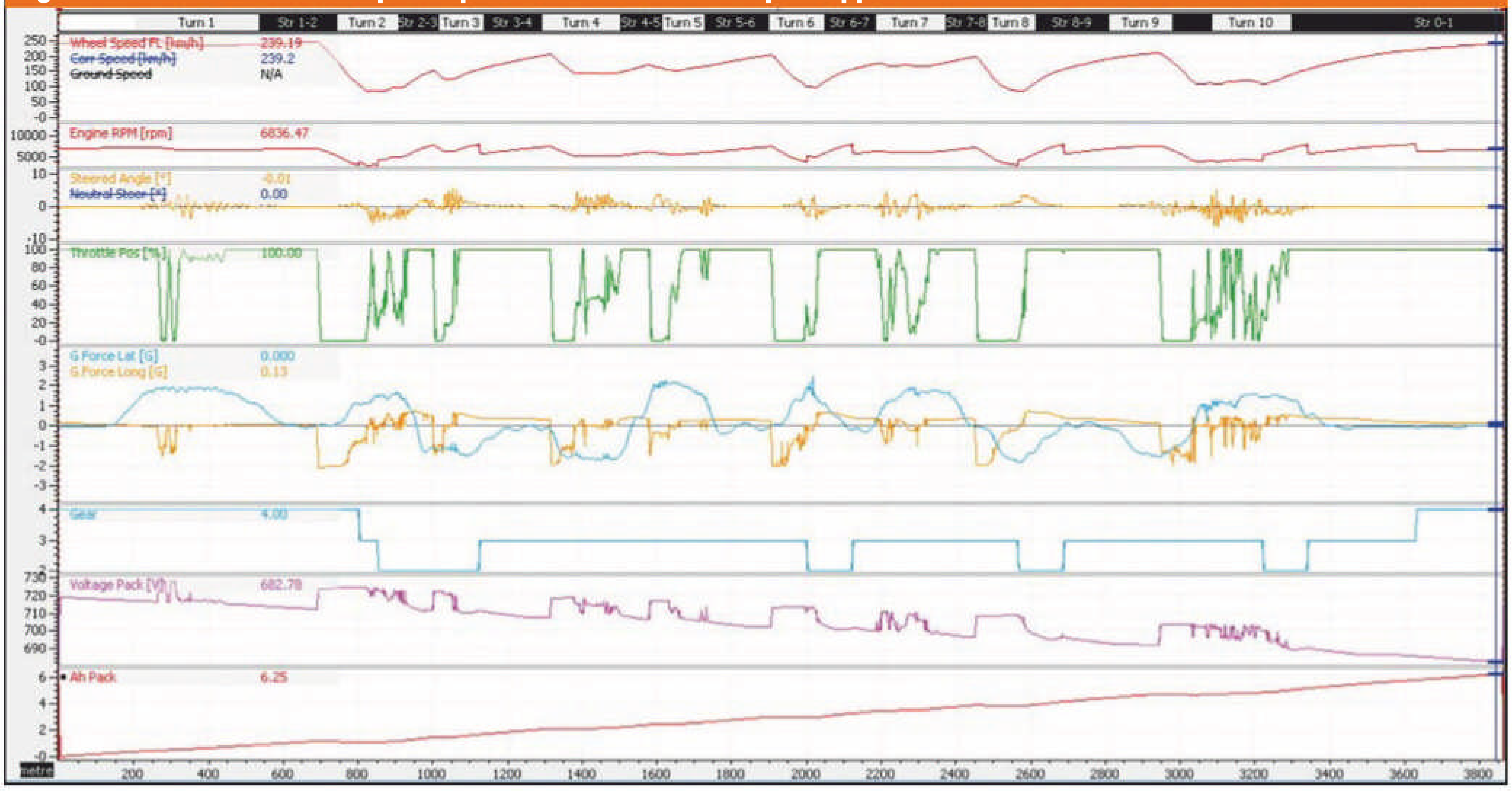


Figure 2: Electric vehicle response parameters for a motorsport application



Let's take this opportunity to review an analysis I did of an ell-electric GT contender at the Bathurst 12 hour with a 380kW motor. Given we'll be running 20 laps over a 45-minute stint, we need a capacity of at least 253Ah. The number of cells required is shown in **Equation 1**. You don't need to be a rocket scientist to figure out a pack mass of 1264.8kg is not practical.

Referring back to the Lotus Elise Time Attack study, even for a sprint event you need a lot of cells in the battery pack. Refreshing your memory with the highlights, we had a working cell voltage of 3.5V and we need a capacity of 38Ah. The pack configuration is given in **Equation 2**. The bottom line is we need 200 cells in series and 10 cells in parallel. This came in at a battery pack price of US$51,000 (approx. £38,170). So even for a sprint event you still need 2000 3.3Ah lithium polymer cells.

Marginal density

What all this shows is that with current battery technology, the energy density is still marginal. As much as some commentators gloss over this, there is no avoiding it. What is driving this, if we go back to **Figure 1** for a road car application, is your throttle being at a generous 10-20 per cent. A motorsport application looks more like **Figure 2**.

As can be seen from the throttle trace in **Figure 2**, you are at full throttle for at least 70 per cent of the lap. This means over 3.8km you will have used up 6.25Ah. And this was for a motor power of 200kW and a battery pack sized for a 15-minute session! This illustrates the primary reason a solely electric battery-powered vehicle will struggle currently at an endurance event.

The other thing this analysis shows is that if the battery pack fails, you are in for a big ticket expense. The current value for a Tesla Model S/3 battery replacement is $27,000 (approx. £20,215). Okay, the battery is rated for 120,000 miles / 190,000km but, should the pack fail, it instantly invalidates the maintenance advantage of electric.

Full charge ahead

The other thing that has been left unsaid about electric propulsion is charge time. Typically, charge rate battery is referred to as C of the battery pack. If you charge at 1C, the battery pack will charge in an hour. If it charges in 2C, it will charge in half an hour. Most modern lithium polymer batteries can be charged at 5C. For longevity, though, you ideally want to charge at 4C, which means it takes 15 minutes to charge the battery pack. For a motorsport application you can get away with this, but if you have electric cars in numbers on public roads, just imagine the tailbacks at the services.

Also, we cannot discuss battery-powered EVs without touching on the charging infrastructure and power grids they plug into. Firstly, if you are going to fast charge an 85kWh battery at 4C, your power usage will be 340kW, or the equivalent of plugging in 140 electric heating fans at full noise. This presents considerable challenges, but not insurmountable ones. What is more critical is the demands this places on the grid.

Depending on where you live in the world, a typical household will use 8-12kWh per day. In a week, around 60kWh. An 85kWh electric car will increase domestic demand by a factor of two at least. This is a significant problem that needs to be addressed.

EQUATIONS

EQUATION 1

$$No\_of\_cells = \frac{V_T}{V_{CELL}} \cdot \frac{Ah_{TOT}}{Ah_{CELL}} = \frac{650}{3.5} \cdot \frac{260}{7.7} = 6324$$

$$Pack\_mass = No\_of\_cells \cdot m_{CELL} = 6324 \cdot 0.2 = 1264.8kg$$

EQUATION 2

$$PackConfig = \frac{700V}{3.5V} S \times \frac{38Ah}{3.8Ah} P$$
$$= 200S \times 10P$$

The other thing that has to be addressed is that in order for battery-powered EVs to have an environmental impact they need to be plugged into a carbon neutral grid. Are the environmentally popular solutions, such as wind and solar, able to achieve this? Let's look at the Australian example. Right now, putting solar panels on your house is a very popular activity, and 6.6kW systems are being actively marketed. The power is there then, but you need to store it. This places even greater emphasis on energy storage, since this turns off at night. That can be somewhat addressed with molten salt batteries, but LiPo batteries will still be required. Once you start to scale globally, this also becomes a major problem.

Environmental impact

Lastly, we need to talk about the environmental impacts of large scale battery production. Some to the political right of Attila the Hun will say flat out that this alone disqualifies electric propulsion. But there are two aspects to this discussion – mining the materials required for battery production and recycling them when they're used up.

In order for battery-powered EVs to have an environmental impact they need to be plugged into a carbon neutral grid

Supplying the raw materials for battery-powered electric propulsions is a concern that cannot be swept under the carpet. Let's say, for the sake of argument, over the next 20 years two billion electric battery-powered cars are built. To make the numbers simple, let's use a battery pack mass of 1000kg. This means we need 2 x 10^{12}kg of raw materials. Presuming demand is provided linearly, if we divide this by 20 that means we'll need 1 x 10^{11}kg of raw materials every year. Turn that into tons and it's 100 million tons of raw materials per year. Or about a quarter of Australia's annual coal output.

The raw materials required for electric vehicles underscores why significant steps still need to be taken in battery energy density. If you throw in the added demand of scaling solar globally, the analysis presented here is highly optimistic, to put it politely.

Putting the focus back on the Toyota Yaris-type EV mitigates the problem to an extent, but it doesn't completely eliminate it.

Interestingly, recycling batteries is not as problematic as some would like to present. The RC community has known for over a decade now that when a lithium polymer has finished its operational life, once it is fully discharged it will readily break down. The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) recently published a feasibility study that showed not only can lithium polymer / ion be readily recycled, doing so represents a great economic opportunity. So, recycling itself is not a huge show stopper.

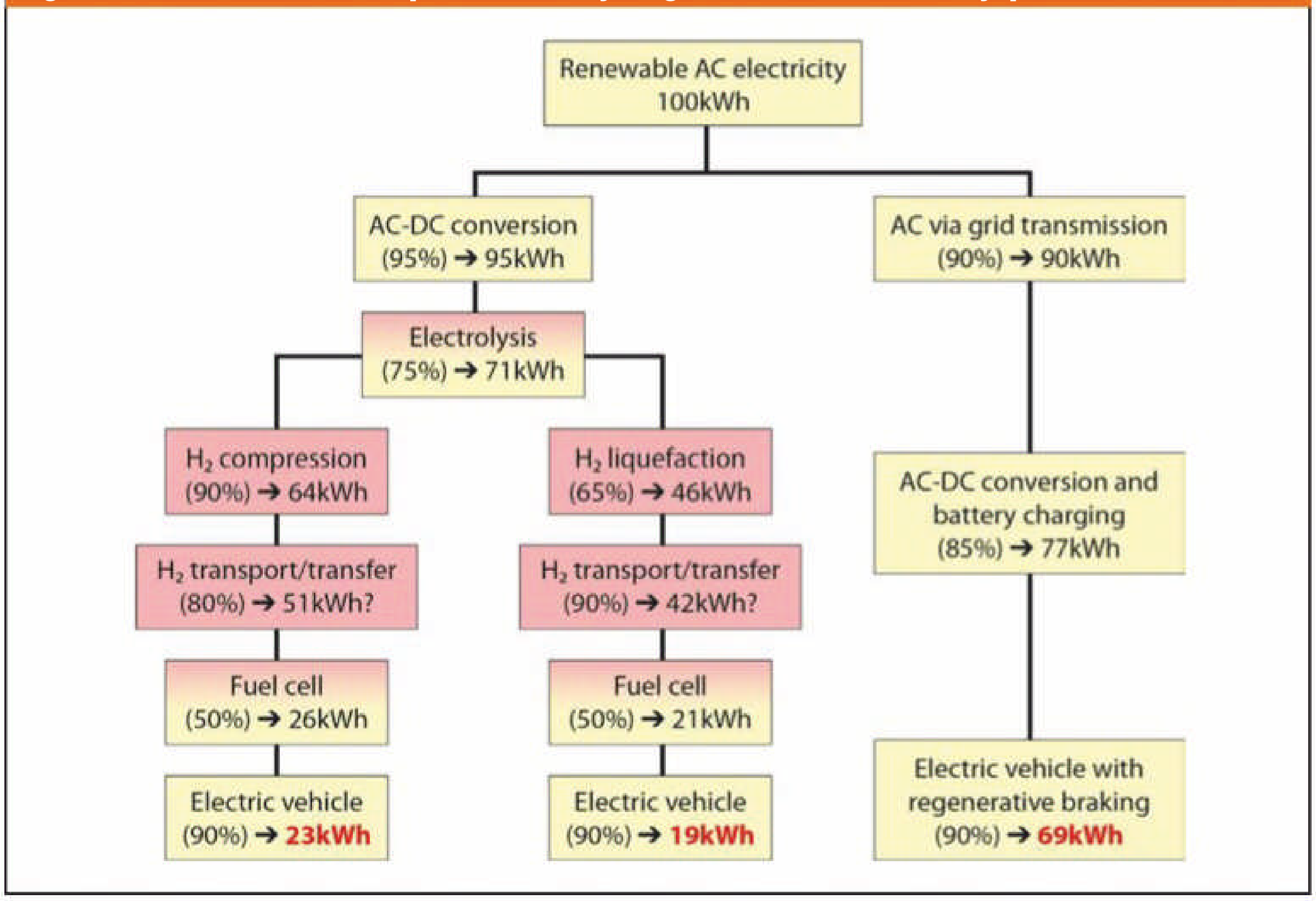
Neither is the argument that electric powertrains are the work of the devil because they don't make that visceral sound that has always been part and parcel of motorsport. Don't get me wrong, the V10s of the 1990s made some of the sweetest music I've ever heard, but I equally enjoy my 3S pylon racer making all the gas planes at my local flying field look as though they're standing still, so it really is horses for courses.

The solution?

The big question, of course, is if batteries aren't the answer, what is? Well, one potential solution to the electric energy density problem is hydrogen-powered fuel cells, and the ACO is getting behind this idea. Largely I suspect thanks to a company called GreenGT, which has demonstrated an LMP2 test bed with this technology on board that weighs 1420kg and has a maximum power of 480kW. Range is stated to be equivalent to its internal combustion engine counterpart and the refuel time is three minutes. However, while the late Ricardo Divila stated in *RE* V29N3 that hydrogen as a gas had an unfair reputation in terms of safety, significant testing still needs to be conducted to validate the technology in motorsport use, particular when it comes to safety.

And hydrogen is not without its difficulties. In his autobiography entitled Skunk Works, the former director of the Lockheed skunk works, Ben Rich, commented at some length on the dangers of producing hydrogen in quantity. This was one of the key reasons the Mach 3 SR-71 was produced with a fossil-based avgas, as opposed to hydrogen.

Figure 3: Devil's advocate position on hydrogen electric vs battery-powered EV



A colleague of mine ran the numbers on producing hydrogen in the quantities that would be required (make no mistake, the volume needed would be in the same order as petroleum) and the energy required disqualifies it as an option. I am happy to be proved wrong on this, but someone needs to play devil's advocate.

Figure 3 is why Elon Musk says Tesla's focus will remain on battery-powered EVs. This could very well just be Elon being Elon, but if I am wrong, I am more then happy for someone to write a reply explaining why.

Before we wrap this discussion up, let me throw in my two cent's worth. The current push for electric vehicles is driven by the climate change debate. I'm aware there is a significant part of this magazine's readership that regards climate change as a hoax, so I'm leaving that alone since it is beyond the scope of our discussion, but there is another reason we need to take electric vehicles seriously, and that is energy security.

Right now, a significant part of the world's fuel comes from the Middle East. It only takes one hiccup in the supply chain from the oil-rich Middle East before we find ourselves in a world of hurt. Having a reliance on any country or region that is not completely stable is at best, risky. That goes for all walks of life, and suffice to say, having all our eggs in the fossil fuel basket is optimistic at best, total madness at its worst.

Conclusion

In closing then, electric powertrains represent a fantastic opportunity for motorsport. Since motor racing will push electric powertrains to their very limit, it allows us to take back the high ground, particularly in research and development. This is sorely needed in our community.

Electric powertrains offer some exciting possibilities in terms of car running costs, throttle response and are the natural choice for sprint events. On a more mundane level, they present a clear and viable alternative for the current class of small, urban car.

However, the battery-powered route also presents significant challenges in terms of energy density, demand on the grid and on the environment in their production. Likewise, hydrogen also offers enticing opportunities, but its production has serious safety implications.

In challenge, though, comes opportunity and we in motor racing can play a leading role in this. In my view, purely through the prism of risk management, the planet deserves the benefit of the doubt.

Technology showcase

Despite the absence of trade shows traditionally held at the end of the year and the start of the next, manufacturers continue to launch and publicise new products ahead of another season of racing.

Here is the latest series of product launches that will help with your racing endeavours in 2021.

GILL SENSORS

4223 liquid sensor

Gill Sensors has a lightweight liquid level sensor that is compatible with fuels, oil and coolants. The 4223 comes with standard and custom mounting options, and has a temperature range of -40degC to +125degC. The standard output range is 0.25-4.75V, but the maximum can increase up to 10V.

The size of the sensor is 100-750mm in 1mm steps and it weighs 36.5g for a 100mm probe with a 1000mm cable, with 0.34g added for every millimetre added.

The probe works with diesel, petrol and biofuels, with hydraulic, gear, motor, vegetable, synthetic ester, polyalphaolefin and polyglycol oils, with ethylene glycol and water coolants, as well as salt water.

For more information, www.gillsc.com

Available in mm increments, the Gill 4223 sensor can be used in a wide range of liquid environments

EEC PERFORMANCE SYSTEMS

e-POD endurance fuel rig

EEC Performance Systems has spent lockdown developing its new e-POD endurance fuel rig intelligent measuring and logging device. The system is made up from individual modules, including rig scales, fuel timer and fuel and air temperature sensors, all of which are battery powered and wireless. They report back to a 15in touch screen PC, which is mounted onto your garage walling.

The software gives simple step instructions to the operator to record each fuelling quickly and accurately. The home screen displays the current amount of fuel in the rig, temperatures and all the data from the previous fuelling. Data records can be sent directly to the engineers via email.

EEC has also made a wireless adaptor, which can be used with existing rig scales.

For more information, email enquiries@eec-ltd.com

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Mod 3 steering wheel

The MOMO Mod 3 is designed specifically for use in rally or drift cars. The deep dish offers the driver maximum control and the yellow leather marker on the top provides a quick reference to the position of the steering.

The wheel is finished in a choice of either black suede or leather, and features two black or two blue aluminium spokes with the MOMO Arrow logo in the centre.

All MOMO racing steering wheels are produced in Italy and are of the highest quality, made with anticorodal aluminium frames and the suede or leather glued to the rim, instead of being stitched, to provide a seamless finish for greater comfort and durability.

For more information, www.momo-uk.co.uk

Rally or drift, the MOMO Mod 3 will help you stay ahead of the pack

XCELDYNE, LLC

Valvetrain supplier expansion

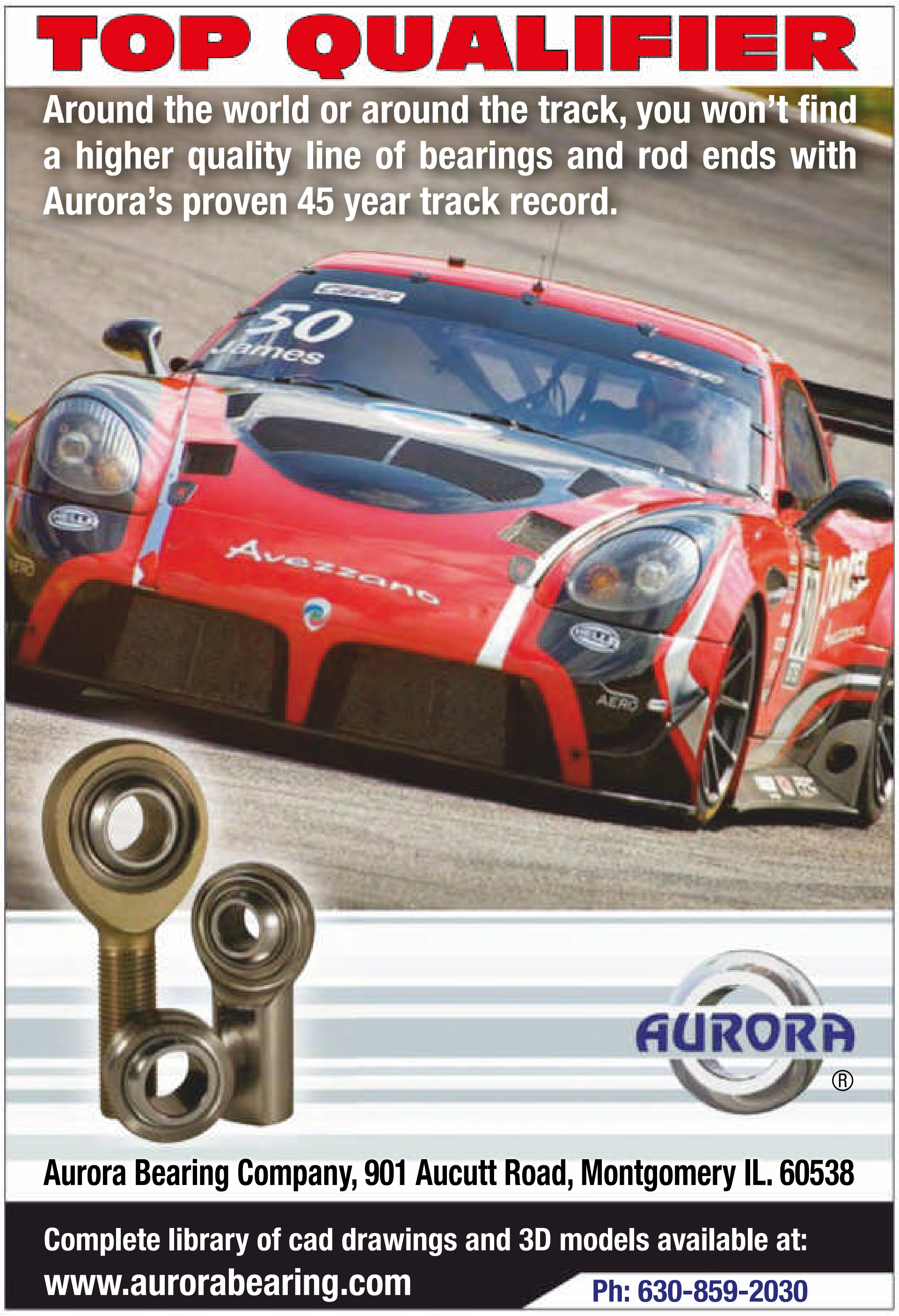
Xceldyne, LLC, a premier titanium valve and valvetrain component manufacturer, servicing the top motorsports teams around the world, has announced it has secured assets of Movaltec Sarl, the premier steel valve and valvetrain component manufacturer in the world, to become the leading global valve and valvetrain component supplier.

The integration of these two highly technical entities accomplishes Smith's and Marteau's shared vision and conviction of strengthening Xceldyne's position in the global motorsports market.

Going into 2021, Xceldyne's expanded product offerings will consist of titanium and steel valves, finger followers, rocker arms, roller lifters, bucket tappets, spring retainers and locators, valve locks, lash caps, valve guides, XTS Timing Systems, PSI valve springs, Spin fuel pumps and wrist pins.

For more information, www.xceldyne.com

By integrating assets with Movaltec, Xceldyne strengthens its position in the motorsport marketplace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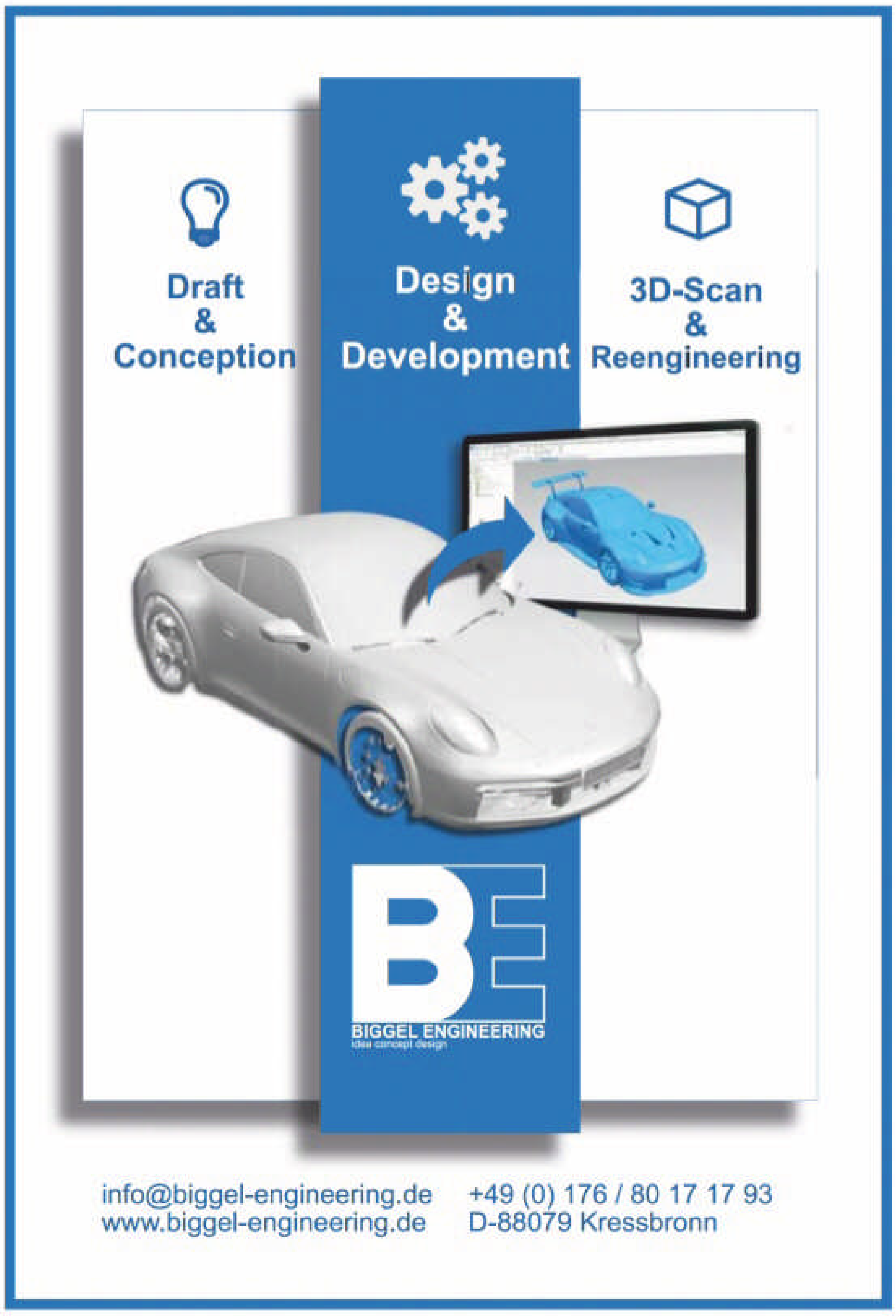
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The acceleration of simulator development

A swathe of race cancellations and a compressed calendar for many championships means teams that had invested in advanced simulation tools are currently making the most of them, with drivers and engineers keen to extract as much benefit as they can.

Some may be surprised at how the current situation has accelerated the use of engineering-class simulators but Kia Cammaerts, who founded Ansible Motion in 2009, is more surprised that it has taken so long for its capabilities to be properly utilised.

That surprise comes from the fact that Cammaerts started looking at simulation while working as the head of aerodynamics at Team Lotus. Although his company hasn't moved far physically, the technology is now on another planet.

Cammaerts started his career at Tiga, working on its Group C2 Sportscars, before switching to Ralt to work under Ron Tauranac on March's Alfa Romeo IndyCar project. From there, he moved to Lotus and Larousse before he started to model suspension, chassis and engine performance that fed into his aero' work.

'Back then, data acquisition and analysis were primitive and, if you wanted to simulate something, you pretty much had to write the code yourself,' he explains.

But as processing power improved, Cammaerts felt simulation was being held back by not having more accurate data of driver performance and feedback. That led to the foundation of Ansible Motion, and an opportunity for F1 teams (Caterham) and later OEMs (Ford, GM, Honda) to access engineering-class, driver-in-the-loop [DIL] simulation tools.

Driver-In-Loop

'When I set up Ansible Motion I felt there was a real need for quality DIL simulators,' continues Cammaerts. 'That led us to create what was the first commercially available, high dynamic motion base simulator for use by engineers specifically for developing high performance vehicles.'

Ansible Motion's route was not to simply take a legacy hexapod, but instead to create a stratiform system that features independent actuation of the ground plane motions. That delivers a more dynamic and increasingly realistic motion capability wherever you are in the motion space. For example, in motorsport if you brake and turn, unlike with a hexapod, Ansible Motion's motion capability is unaffected by the order in which you do things.

While many simulators used by drivers are static, Ansible Motion has continued to develop larger systems for its dynamic simulators.

Despite the advances his company is making, Cammaerts is adamant there remains significant potential for simulation tools to develop.

An Ansible Motion simulator will be used in FE in 2021

Its own R&D facility in Hethel, UK is testament to that, and is currently looking at head-mounted displays, direct links to engine dynos in other facilities and the ability to simulate the climate, as well as the best ways to simulate electric vehicles. It's obviously doing a good job after recently concluding a deal to supply a new simulator to a Formula E team in 2021.

Ansible Motion is set to announce publicly its new dynamic simulator in early 2021, having already taken orders 'off plan' from customers eager to ensure they stay at the cutting edge of simulation. If 2021 is anything like 2020, that sounds like a very forward-thinking idea.

ansible motion
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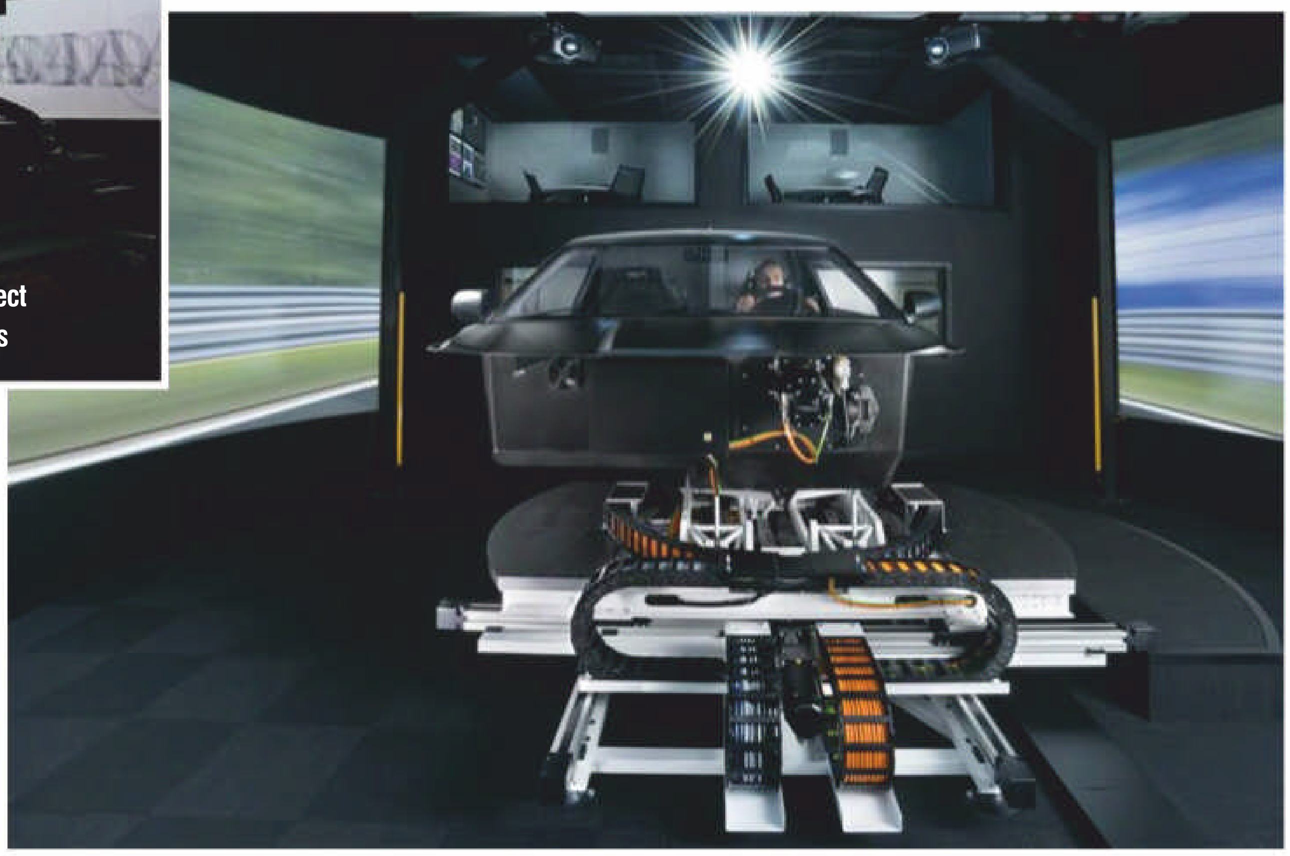
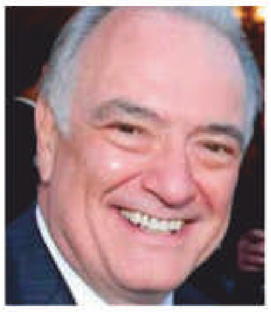
Simulation still has huge development potential, including direct links to other engineering facilities and environmental controls

A more dynamic and increasingly realistic motion capability wherever you are in the motion space





All change

2021 will present a raft of new challenges. Are you ready to accept them?

Welcome to an exciting new decade, when businesses see change as both a challenge and an opportunity for positive action. We face change on a scale unseen in most lifetimes as the world, urgently and determinedly, rises to meet environmental and economic challenges.

Opportunities will arise when the UK becomes an independent nation on January 1, eager to make productive trade deals around the world. With such freedom comes challenging new limits and regulations, which we must learn to live with if we are to grow our businesses.

Motorsport is relatively secure, having taken some action already – major series restricting budgets and offering more value to sponsors, audiences and participants. We have six months or so to rebuild revenues to reasonable levels as our sport becomes re-established after the pandemic. The next challenge will come in nine years, when many countries where motorsport is well established ban the use of internal combustion engines in new vehicles.

I expect the current survival strategy, focussed on cash security and restoring revenues, is likely to dictate business decisions and investments throughout 2021. I understand that motorsport revenues in most major markets will have reduced by at least 33 per cent on 2019, though in hospitality and circuit operations this could be as high as 80 per cent.

The UK, as it recovers from the pandemic, where the speed and effectiveness of vaccines is critical, faces major changes in attitudes of society, international trade, employment and human behaviour, and business leaders must move quickly to respond to these challenges and effect change to survive and prosper.

Competitive nature

I'm confident the agility, quality and competitive nature of those involved in motorsport and high-performance engineering will serve us well in the coming months and years. The ability to embrace and respond to change rapidly is essential to success in the competition of motorsport. This attribute will be needed in almost every aspect of our future business lives.

Even re-engaging employees brings new challenges. Some are scared and cautious about returning to work alongside other people. Employers will have to create a caring, but commercially efficient response to this so success can be delivered and future employment secured.

Whether by train, 'plane or car, we will still need to travel to rebuild business at home and abroad. Our small island's GDP relies on international trade, the European continent being our primary market, alongside the USA. Trade deals or not, we need to re-engage with our customers and re-establish success.

Building revenues requires face-to-face interaction to re-energise relationships. We can't rebuild our businesses purely online, or via Zoom. Changes have to be made and compromises reached. Yes, more challenges.

Jamesteohart | Dreamstime.com

There is light at the end of the road ahead. Be prepared

The long lay-off has affected some employees' attitude to work, and there will undoubtedly be pressure to change hours, places of work, to increase online activity and be more flexible. Careful consideration is needed if employees are to happily return to full productivity and efficiency.

All have welcomed free funding support from the government to help us survive, but the repayment of that apparent generosity will start soon. In addition, substantial funds are needed to deliver the plans for zero-emission transport in just a few years, so we can expect increased taxes as businesses and individuals, and need to be prepared for that.

Wise, UK-based companies will already have checked their suppliers' capabilities post-Brexit, and created a ghost list of UK-based suppliers who could replace imported lines, keeping them on standby if difficulties arise. A tiny component can easily hold up a major project, so having such insurance in place is common sense.

This is a good time to consolidate to mutual benefit. I expect an increase in the number of takeovers and company re-structures, some by collaborating with previous competitors.

It will be useful to review the cost and size of business premises as landlords are now more willing to accept sub-letting. This allows offices or factories to be split into useable areas to meet increased demand for smaller premises and to maintain rental income.

Funding growth

We can expect funding from government for a wide range of R&D-based projects embracing the new environmental challenges and lifestyles. Businesses should plan to commit time and resource to securing free funding to cover a range of business growth activities.

The UK's relationship with other countries will very soon change, and increased exporting will be essential to many businesses. We are likely to import less from the EU and rely more on UK capabilities, but export more to countries open for new business.

In the immediate future, R&D companies in motorsport and high-performance engineering can benefit from the new legislation to kill off fossil-fuelled transport in nine years. Already many in Motorsport Valley deliver energy efficient solutions to various sectors. They could secure rapid growth from new opportunities and investment in R&D, collaborations with new partners and new motorsport series. The environmental challenge is now a priority, where words will be turned into action and deliver real business.

This exciting future will be full of opportunities. We must rise to capture these quickly and with confidence, using our world-class capabilities earned from supplying the highly competitive and demanding world of motorsport for many years.

The MIA has been inundated with business enquiries throughout lockdown, all asking for our help to find new business opportunities and revenue streams. Please contact us – www.the-mia.com – as we are here to help not only our members, but the wider motorsport industry, secure the success it deserves.

In the meantime, I wish you all a happy, exciting and prosperous New Year.

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Year of the long knives

As manufacturers desert the sport in droves, an opportunity arises

Manufacturers have started the challenging process of re-aligning their racing activities, and the next few years the racing world will look very different. Honda announced its withdrawal from Formula 1 at the end of the 2021 season, and Porsche stepped back from the US GT racing programme, but there was far more to come in December.

Audi announced it will withdraw from Formula E to concentrate on the rather lower profile Dakar rally with an electric car, and return to Le Mans with the LMDh, looking more than ever like a customer racing programme. VW then announced it will withdraw from motorsport activities entirely, impacting the WRC and the Pikes Peak ID.R.

Next, BMW followed up on its announcement that it will withdraw from the DTM (which has already lost Mercedes and Audi) as well as Formula E. The news continued… Bentley pulled out of GT3 as a manufacturer, apparently to send a clear message that it no longer wishes to race with an exclusive internal combustion engine. More news came from within the VW Group, as Porsche announced its return to Le Mans, again on the IMSA-inspired LMDh platform.

A new chapter

The re-alignment is not the disaster for motor racing some might have us believe. It is merely the start of the next chapter in the sport. The Covid pandemic may have accelerated the trends, and it was already clear that motor manufacturers were over-extended in their racing activities, pushed by new technology, unsustainable costs, limited return on investment and technical regulations that encouraged the introduction of new technology, but then locked it in for long periods of time, stifling development.

The consistent drive towards alternative powertrain technologies, demanded by the manufacturers and delivered by governing bodies, has driven up the cost of competition to a level that was never sustainable, at least not without an incredible escalation in return, and that simply never arrived.

What the pandemic also brought about was the rise in e-sport. On the face of it, this is perfect racing. No one can get hurt, everyone can join in, and the graphics are good enough to imitate real racing. The skills needed to be competitive are as important as in a real car, and the environmental impact is negligible compared to a regular race. But yet, it's boring. The excitement of the senses is not there as it is at a genuine racetrack, and I for one hope this phenomenon is killed off as rapidly as it has arisen.

Should the Covid vaccine work, there should be no reason why racing cannot return to a more traditional season in 2021. Mass people migration is now clearly manageable, fans want to return to the track and teams still need to race. They have built a business around it. The question is, what should spectators expect to see racing?

Manufacturers suffered in 2020 with production lines closed for months, leaving product short and profits down, so it is no surprise to see them prioritise money making over money-spending activities. I do wonder how the FIA and other organising bodies will react. Will they continue to pursue the high-technology, low-cost route, or will they reduce costs, and breathe gently on the glowing embers of suppliers to prove their products in competition?

Break away

Now is the time for privateers, and the regulations need to relax to encourage companies to race in all levels of the sport. Now is the time to break away from the trends and return the focus back onto competition rather than technology development. For promoters, filling the grids will be as important as it will be to fill the grandstands, and the only way to achieve both is to provide great racing.

While manufacturers take a step back from factory racing programmes, now is the time to evaluate whether or not they should be driving the new regulations. I think not. They have their place to race, but they should never have been put in the driving seat and become so powerful. They have written regulations they can take to their boards and sell, choosing one or perhaps two, but not all of them. And as manufacturers take their decisions, so series rise or fall. Now is the time for stability, and that has always come from the teams, not the manufacturers.

> **Now is the time for stability, and that has always come from the teams, not the manufacturers**

I hope, for the sake of the sport, that this situation leads to an end to globalisation. That national identities can return to domestic series, including Super GT, Formula Nippon and, crucially, Formula 3. I hope chassis manufacturers are welcomed back into competition, that technical development can take place on every level of the sport driven by suppliers, not manufacturers. This may be my Utopia, but I think this is a golden opportunity.

ANDREW COTTON Editor