CYBER WARS: How McLaren F1 analyses billions of data points – p14

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Formula 1 2022

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Austin Cindric leads the pack on his way to victory in the Daytona 500, which took place in mid-February and was the first race of the Generation 7 NASCARs

Getty Images

All that glitters

Initial thoughts on the emerging 2022 Formula 1 contenders

Surely this is the most nerve racking, yet exciting time for F1 design teams in years? The long-awaited new breed of Formula 1 cars being revealed as I write do, actually, present quite major differences in appearance, even if camouflaged to some extent by the launch liveries and acknowledging the desire for retention of secrecy concerning some features.

The ridiculous and hugely costly to develop bargeboard arrays have been banned, and the 2022 cars look sleeker and less bizarre as a result, if not quite as stunning as the futuristic images doing the media rounds a couple of years back. Ironically, however, the most radical and important design features – bearing in mind that these are responsible for at least 50 per cent of the overall car downforce – are the ground effect venturis, which of course cannot be seen. Certainly, the subtle shaping of these to achieve the optimum downforce at different speeds, without the centre of pressure migrating unfavourably under braking and acceleration, has no doubt received a great deal of CFD and wind tunnel attention. As with engines, though, peak figures do not always translate into the best on-track performance.

Cool runnings

Unsurprisingly, sidepods and engine covers appear to vary the most in designers' initial interpretations of the 2022 regulations, mainly driven by varying PU cooling requirements and their solutions. As always, these external aerodynamic surfaces are a compromise between keeping temperatures of the hybrid package within tolerances, minimising drag, achieving the desired weight distribution fore and aft and keeping the car's c of g as low as possible.

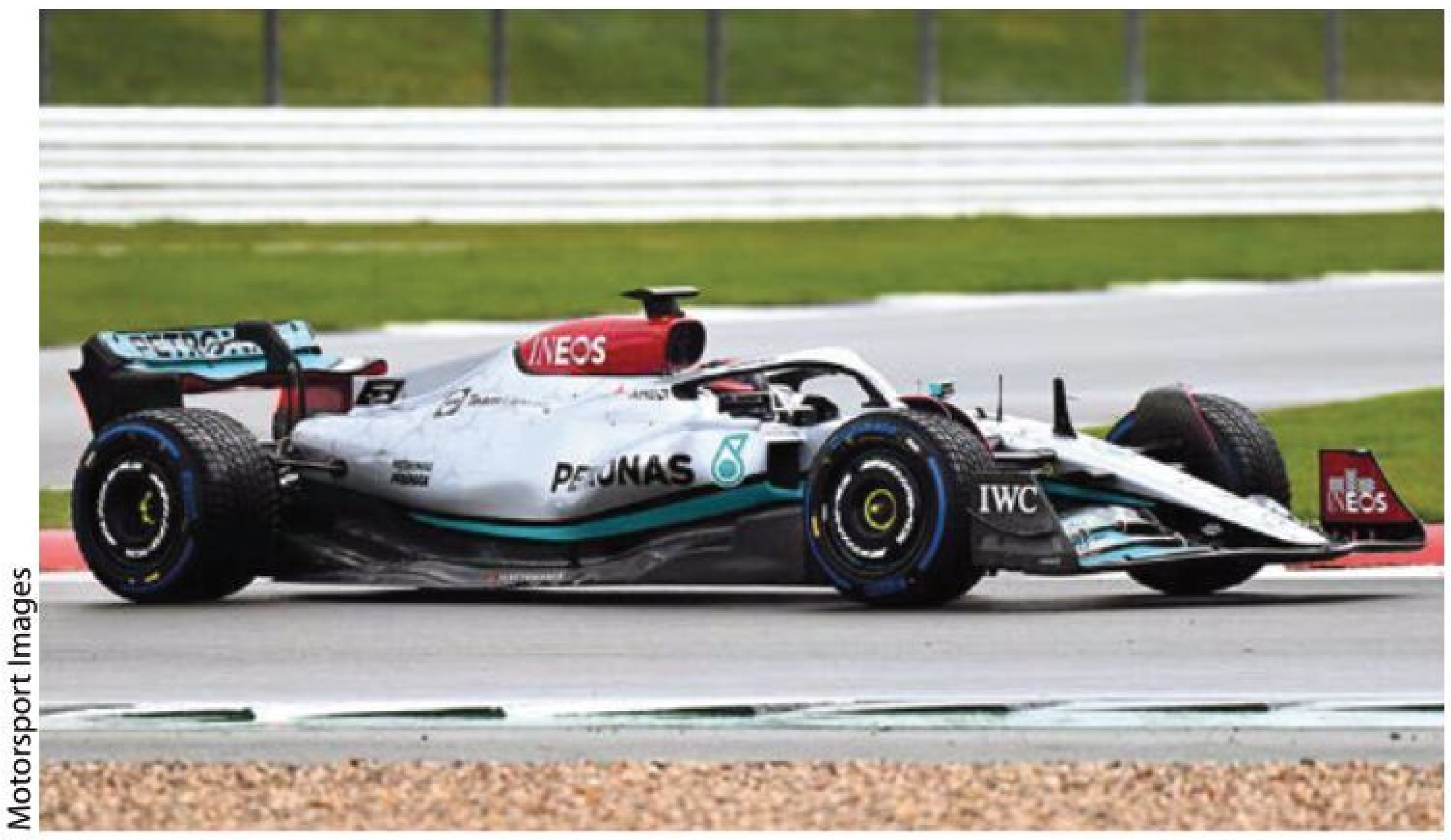
Packaging is, of course, a fundamental issue within the overall layout, and minimising weight is always a given. This is not to say that one concept is going to prove superior to all the others – there can of course be more than one way to achieve a similar level of performance – but certain design features from the most competitive cars will doubtless become more generally adopted as the season progresses.

Without question, a great deal of effort will be expended by teams using sophisticated photo techniques to spy on their rivals, just as Racing Point did to mimic the 2020 Mercedes W10.

Nonetheless, one cannot envisage significant changes being made involving the monocoque structure and fundamentals such as the chosen wheelbase, unless a team's situation is desperate.

Bolt-on goodies

Timeframes, and the budget cap, mean developments must be limited to bolt-on / off appendages, examples being wing assemblies and parts controlling airflow to the underbody venturis, possibly even the venturis themselves. There will be a myriad smaller revisions and I expect many to be around the rear of the cars as engineers get to grips with the testing feedback.



Motorsport Images

As this photo shows, one thing that has not improved on the 2022 cars is driver visibility

Achieving the best interaction of all elements in that area that can contribute to downforce is vital. There are distinct probabilities of components appearing that are missing on the launch cars. Williams' FW44, for example, looks distinctly unfinished around the Coke bottle and rear tyre area. The Ferrari F75 front wing assembly appears deliberately anodyne. Red Bull has been playing games and I simply can't believe the Haas renderings revealed so far.

As usual, most attention focuses on the aerodynamic stuff, but mechanical design is extremely important, too. I confess I'm puzzled by what seems to be a common theme: that the spring / damping will need to be a lot stiffer than before, because ride heights will be lower to maximise the ground effect. Well, except for the Red Bull philosophy of ungainly high rear ride height, though that's likely to be gone in the new generation car.

I cannot see how cars can be run much closer to the ground than before, judging from the sparks that regularly streamed from front skid blocks. Yes, the greater sidewall rigidity of the latest low-profile tyres will enable chassis to be set a little lower statically, but the final dynamic clearance will surely be similar, especially as there is supposed to be a reduction in overall downforce under the latest regulations.

In fact, the pitch sensitivity that is endemic to a flat-bottom surface should be reduced considerably by the adoption of the ground effect underbody tunnels, their behaviour in this respect being inherently more benign.

Enough compliance for drivers to be able to use kerbs without completely upsetting the car will still exist. So will managing temperature and degradation of the 2022 Pirelli tyres without the benefit of some of the past clever gizmos.

Suspension generally should assume prominence in the scale of performance factors, so I really don't 'get' these go-kart allusions. As for predictions that these cars will be harder to drive. Well, once a mechanical and aero balance is achieved, *any* car should be decently driveable, especially with the PU power and torque delivery characteristics staying largely unchanged. But bring it on and we'll see. Let courage and talent shine through!

With barely a shakedown having taken place as my deadline closes, the only real on-track driver feedback so far echoes what was already evident from the simulator work: visibility is poor, due to the larger front tyres and air deflectors. I've written before how bad the drivers' view is already through the 'letterbox' bounded by high monocoque sides, low seating position and the Halo strut. To add another restriction isn't good, and to my mind it's dangerous.

Given the 2022 tyre is only 60mm greater in OD than before, I suspect the main problem lies with the deflector. Maybe this will have to go then, or be revised? Shucks, valuable sponsor space gone along with it…

The big question, however, still remains. Will the racing be improved? Probably, but 'difficult to follow closely' will likely remain an easy driver excuse for not trying harder.

I cannot see how cars can be run much closer to the ground than before

Ground force

After years of planning and a Covid-induced delay, the new generation Formula 1 cars finally took to the track. Racecar Engineering *was on site to see the first of two pre-season test sessions and offers its best guess as to what the teams have been up to*

By STEWART MITCHELL

XPB

The 2022 Formula 1 World Championship cars turned a wheel for the first time at the Circuit de Cataluña on 23-26 February this year. It was here the new era of the sport began, and the teams got to grips with their new machinery, designed to all-new chassis and aerodynamics regulations.

The 2022 technical rule book defines a specific flow field and wake pattern for the car's aerodynamics to follow – a vast departure from all generations of Formula 1 before it. The rules also limit the number of aerodynamic devices teams can put on the car. Because of this, teams are forced to be more efficient in the design phase, asking more of their engineering choices, rather than just adding as many features as possible to extract maximum performance.

With a completely new aerodynamic shape, the cars perform entirely differently. Consequently, much of the aerodynamic understanding teams have accumulated over the last few decades has been put to one side.

Additionally, the way the rules are written is also new. In the previous generations, designers were given boxes to design elements inside. As more loaded surface area means more downforce, the aerodynamic features would typically run up to the edges of the boxes, forcing a vertical and horizontal interface at the corners.

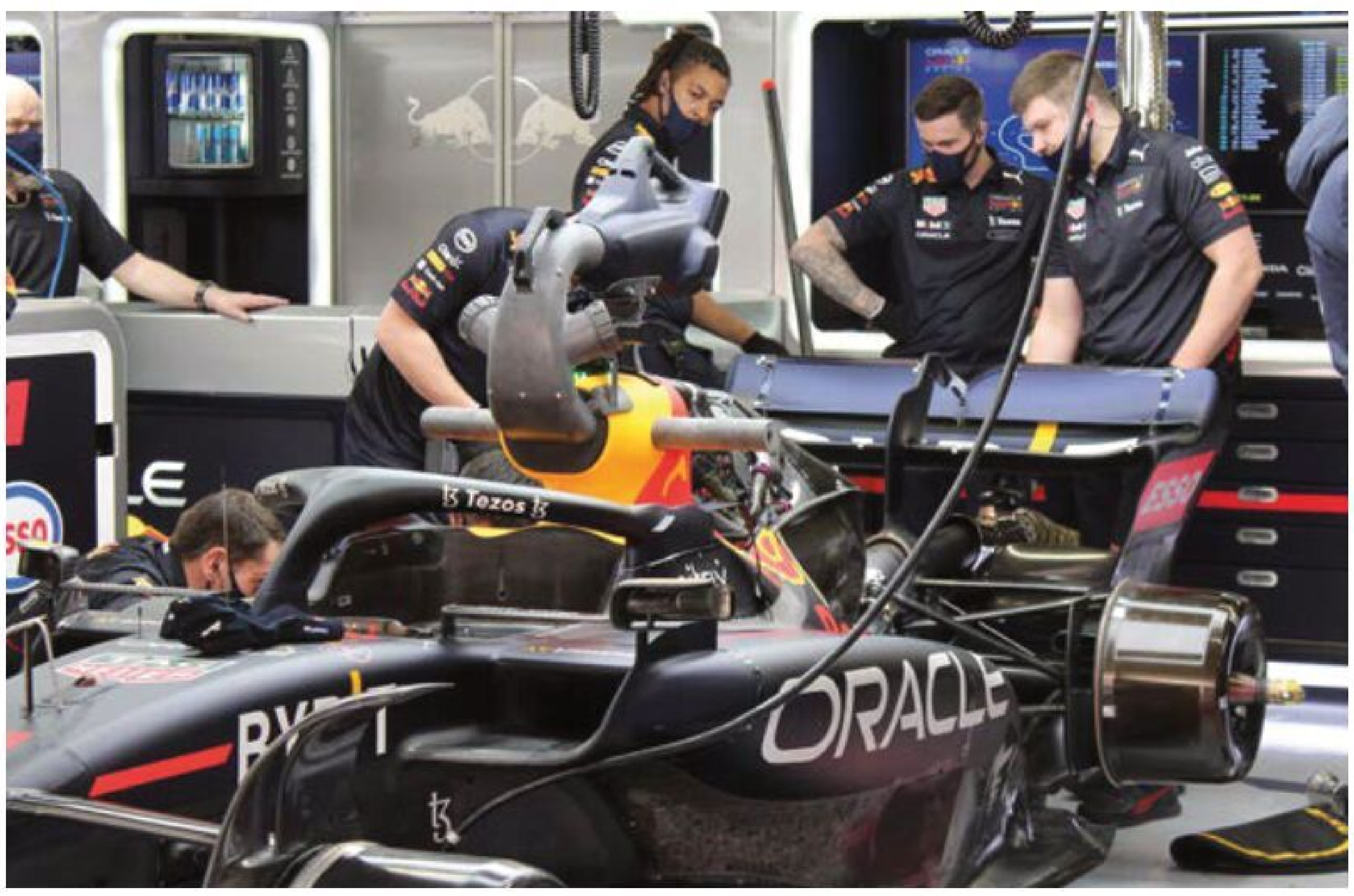
The new regulations are written around prescribed CAD surfaces, and teams must design within specific tolerances to these. This rule-writing technique means teams' approach to adhering to them had to change, too. The most dramatic result is that the 2022 regulations turn many of the 90-degree intersections into sweeping radii.

Vastly different interpretations of the new rules could be seen up and down the paddock straight off the bat, with teams' engrained engineering and aerodynamic philosophies shining through. The way each team wants to achieve the FIA-desired flow field, and its dependence on each aerodynamic feature, power unit

The most aerodynamically influential part of the 2022 Formula 1 cars is the all-new floor, marking the return of ground-effect cars to the sport

The 2022 Formula 1 technical regulations see the biggest changes to the rules in the history of the sport, and how they have been interpreted is vastly different throughout the paddock

Engines are largely unchanged from last year, but the new aero rules have forced teams to re-think their cooling packages, as seen here on the Red Bull RB18



Stewart Mitchell

manufacturer, ancillaries and cooling system layout, even its technical partners, clearly influencing the final product.

Ground effect

The most aerodynamically influential part of the 2022 Formula 1 cars is the all-new floor, marking the return of ground-effect cars to the sport. As there aren't many series that exploit this level of physics, most contemporary Formula 1 aerodynamicists will never have worked on ground-effect cars before, so there is likely to be a significant learning curve for the teams here.

There's also not much to be taken from past generations of Formula 1 cars

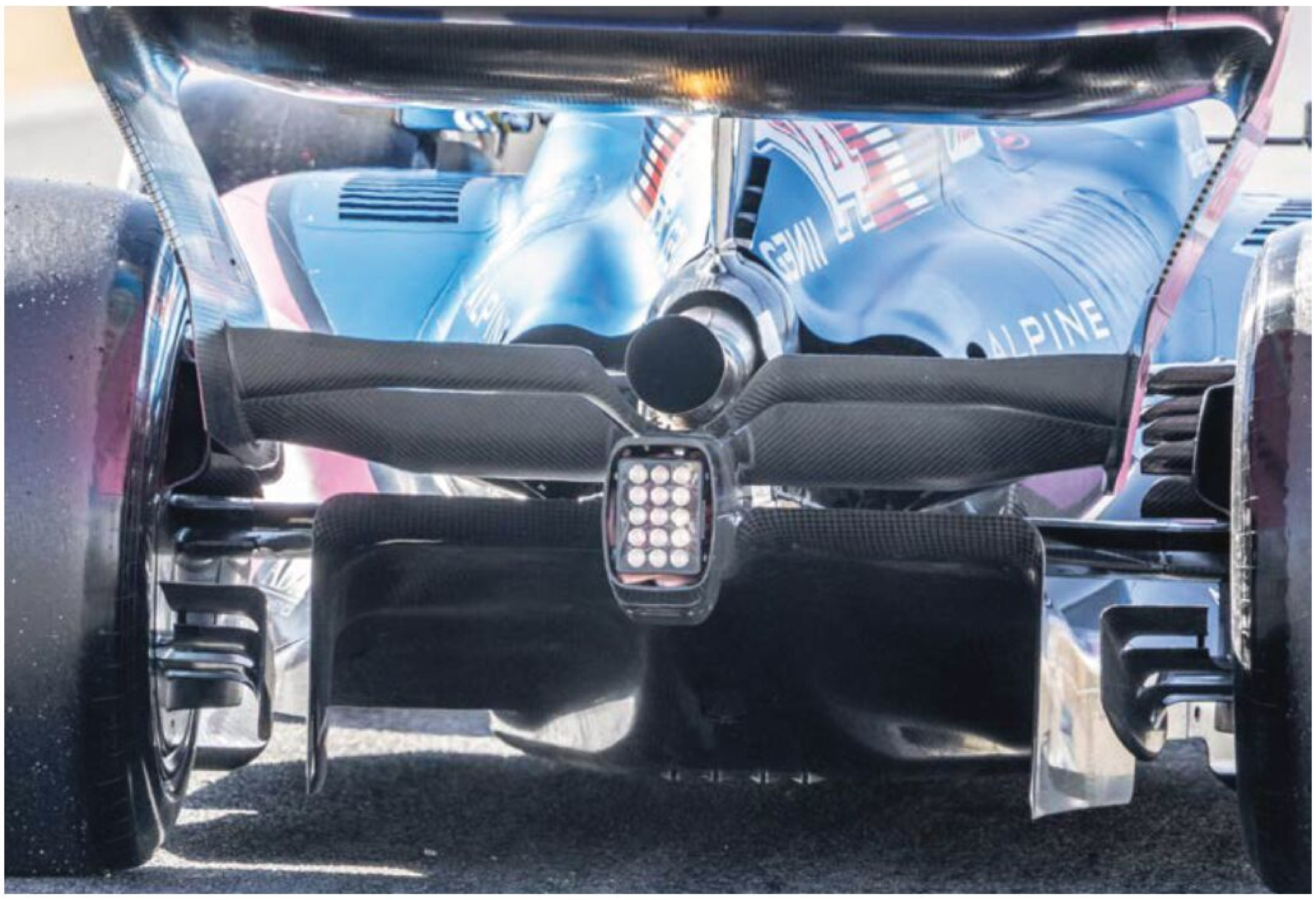
The 2022 Formula 1 floor has a curvature to it, generating a low-pressure venturi zone rearward of the car's centreline

that exploited ground effect (the late 1970s to early 1980s) either, as the level of aerodynamic understanding was minimal back then, compared to what it is now. The quality of simulation tools, including CFD and in the wind tunnel, are light years ahead, too.

A ground-effect car works by using tunnels in the car's underbody to produce downforce. When it rolls over the ground, there's a boundary layer at the track surface where the flow under the floor is greater than free stream flow, lowering its pressure and generating downforce.

The 2022 Formula 1 floor has a curvature to it, generating a low-pressure venturi zone rearward of the car's centreline. Even though the rules allow for a significant volume window ahead and behind the throat of the venturi, there is a minimal area between those bounds of freedom. The upper and lower curvature bounds must stay within limits prescribed in the rules.

It wasn't possible to see what direction teams developed the floors during testing, but it is clear from the way the regulations are written that there is much more space to play with towards the front of the tunnel, specifically how steep the entry is and how quickly teams want to compress the air into the tunnel.



Lawrence Butcher

Small fences energise the flow within the boundary layer on a micro scale, seen here on the post-venturi floor of the Alpine A522

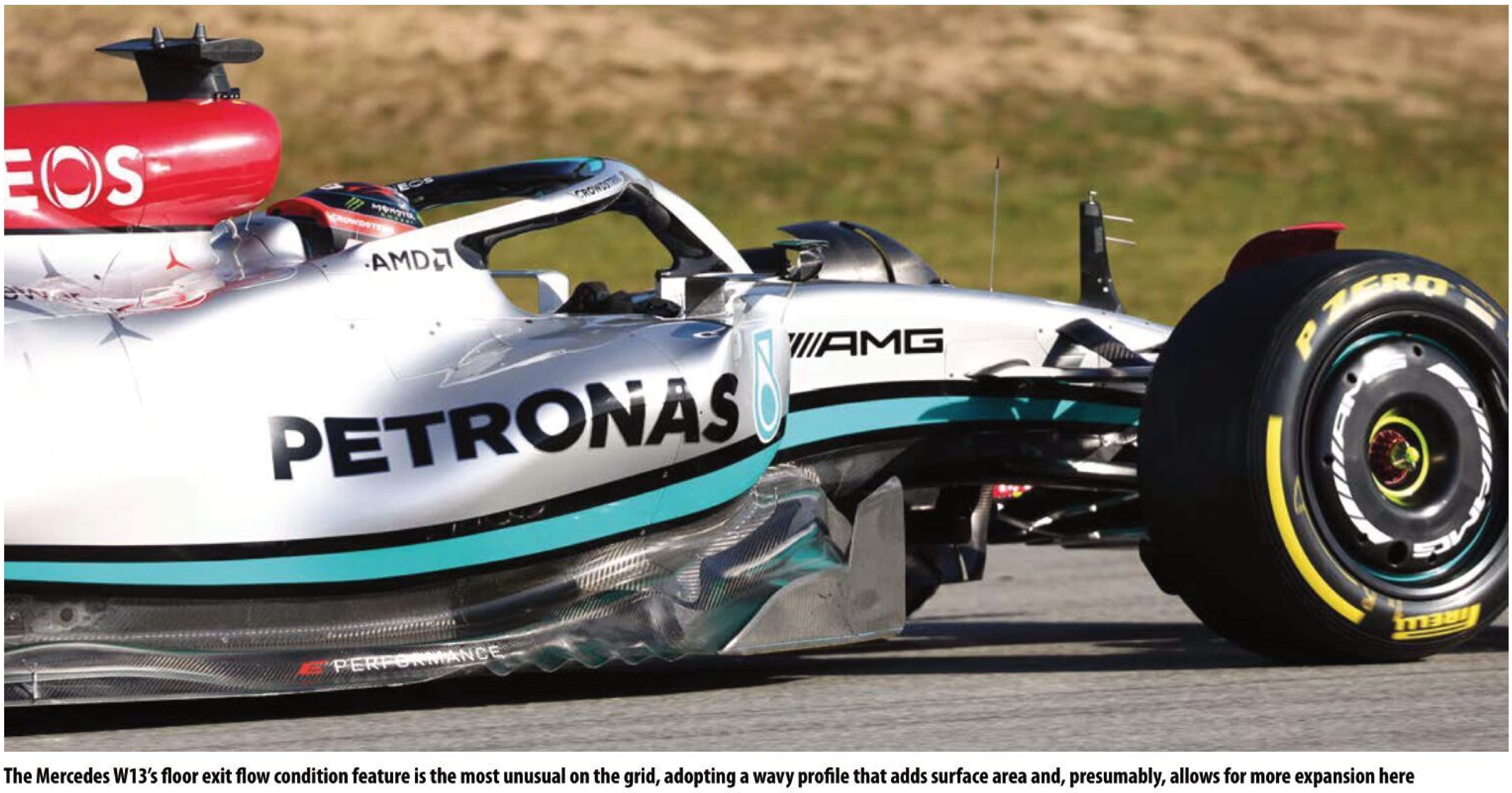
From the outside, cues as to the shape of the tunnels on any of the cars were limited, though there are clearly several different interpretations of the best way to handle this.

Floor fences

The entrance to the floor space is volatile. Teams must control the behaviour of the air stream there very accurately, and very quickly. Instead of just bringing ground-effect floors back and leaving teams free to add vortex generators, winglets and other kinds of aerodynamic furniture, the rules restrict development to floor edge wings and fences.

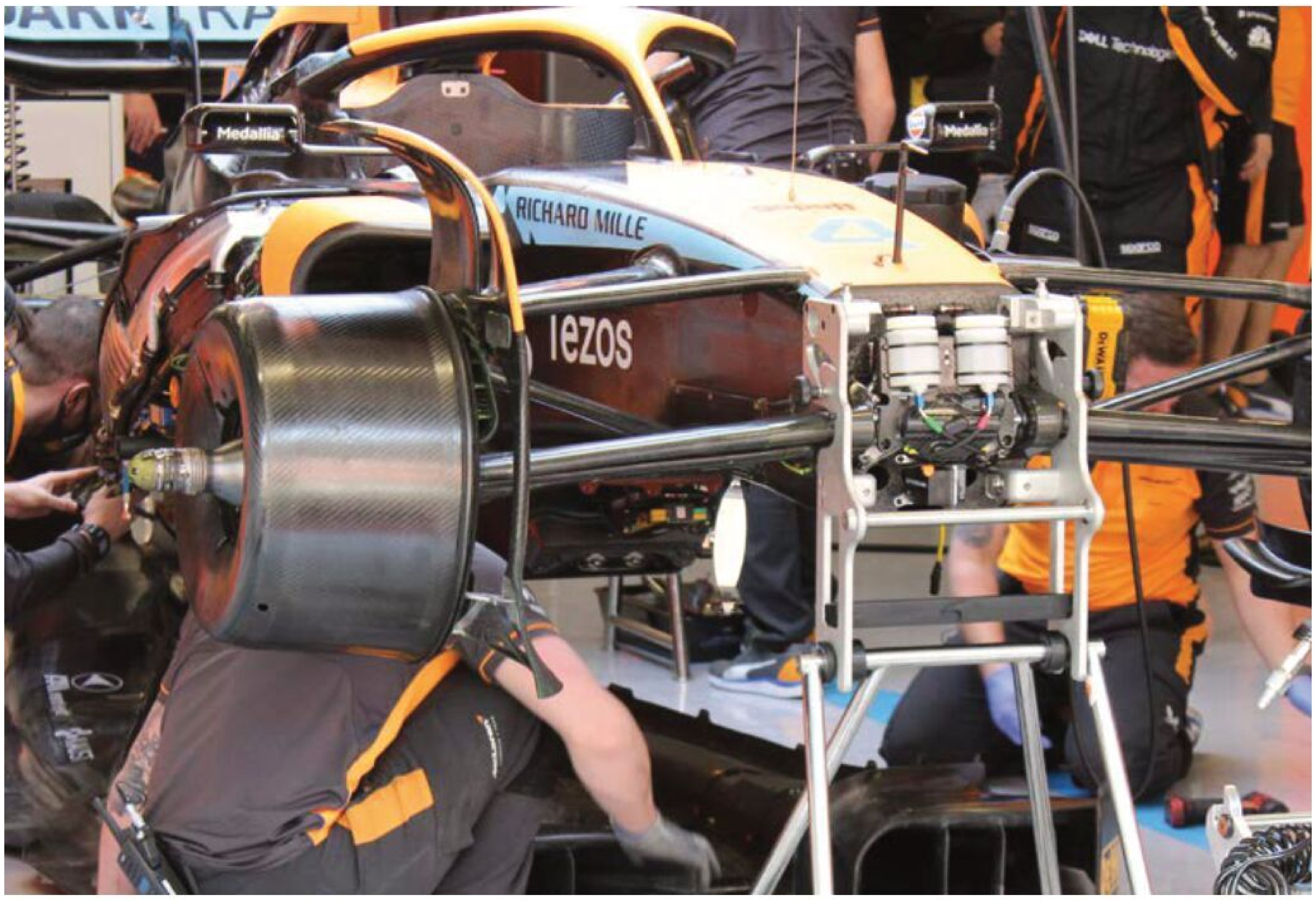
Depending on design philosophy, teams must decide whether they use the floor fences to deal with the front wheel wake, create vortices to add energy to the air under the floor or a hybrid of both. The floor fences rotate the air to generate more energy into the floor flow, creating a pressure difference across the face of a floor fence, which can make a vortex that runs into the floor, adding momentum to the boundary layer and extracting more downforce out of it.

As fences transport momentum from some space of high momentum into the ground boundary layer, their primary effect is



The Mercedes W13's floor exit flow condition feature is the most unusual on the grid, adopting a wavy profile that adds surface area and, presumably, allows for more expansion here

Stewart Mitchell



The floor of the McLaren MCL36 highlights the team's interpretation of how to best manage the flow field entering the tunnels

Depending on design philosophy, teams must decide whether they use the floor fences to deal with the front wheel wake, create vortices to add energy to the air under the floor or a hybrid of both

to maintain the desired flow field for a steeper exit angle of curvature at the back of the car. The consequent expansion out the back will subject that boundary layer to a steeper pressure gradient, creating more downforce.

Of all the Barcelona test cars, the Mercedes W13 and AlphaTauri AT03 featured the most pronounced and forward protruding floor fences. Most of the other cars had fences concealed by the tunnel's outer edge. McLaren's front floor fences, for example, sit on the same plane as the front floor edge, suggesting a different tunnel entry regime.

The rules prescribe the position of one of the front floor fences, and then a maximum number of additional fences allowed. However, as teams add to the fence count, so drag increases from the shed vortices, so there is a trade-off to be managed for the extra expansion they create at the back of the floor.

Understanding where drag originates and hurts performance, how strong the vortices are and whether there is a need to shed these to hit the maximum curvature allowed by the rules is therefore a critical area of development and teams will have worked hard over the last few years to understand and exploit the regulations to their advantage.

Floor edges

The floor edges are another crucial area of development because here's where the ingested air can severely reduce the performance of the floor. Several teams have designed devices to put on the outer edges of the floor where permitted.

Many of the cars seen at Barcelona have a section of upswept outer floor edge, around halfway down the car in the front half of the floor. This is presumably an exit flow condition device although without seeing the full aero map of the car one cannot be sure.

The exit flow feature helps maintain the desired flow field under the floor and, as a side effect, should generate local load at this point without putting too much loss into the flow that may impact the car's rearward flow field. Any flow not ingested into the tunnels comes out sideways from underneath the floor at this exit feature, into a stream beside the sidepod area.

Again, these exit flow features are different for each car, coinciding with the teams' overall aerodynamic philosophies.

The Red Bull RB18 is arguably the most extreme interpretation of the 2022 rules, with a heavily under sculpted sidepod design. Note the track rod of the front suspension swept far back and mounted significantly lower than the push rod

On the Red Bull RB18, for example, the exit flow device location is much further back than the other cars, suggesting that underbody flow separation doesn't occur until further down the car, compared to the other cars carrying this device.

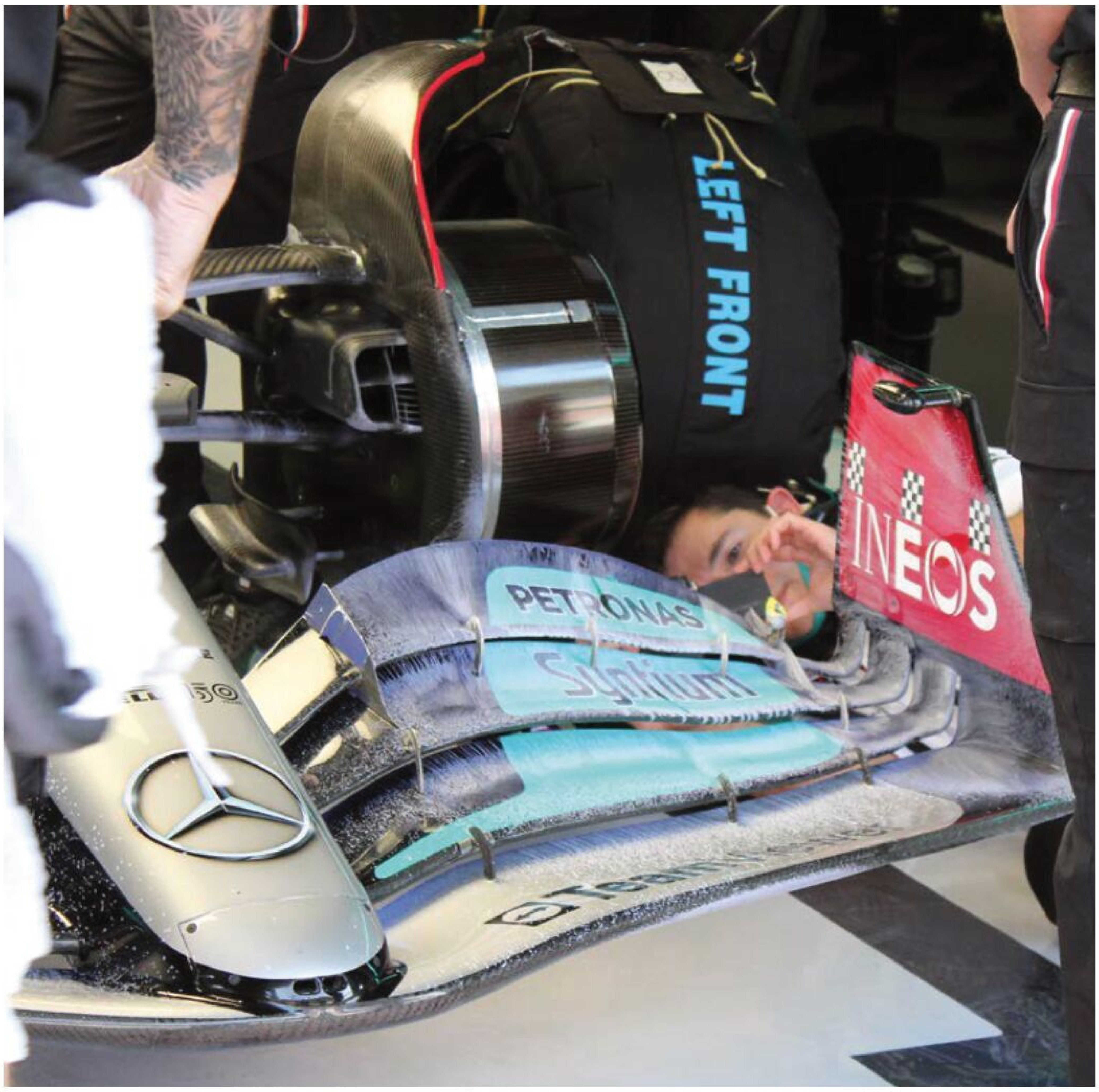
On the Mercedes' W13, the treatment of this area is unique, its outer edge adopting a wavy profile, which adds surface area and presumably increases expansion here.

AlphaTauri (AT03) and Aston Martin (AM22) both have their own interpretation of this feature, the cars' devices showing different curvatures and shapes.

Diffusers

As far as diffuser geometry is concerned, it's very prescribed in the rules, with flat walls, no significant outwashing and tunnel exits that shoot the under-floor air straight back. Expanding it laterally, as per the previous regulations, which would create a much wider wake, is no longer permitted. Consequently, many of the little tricks teams previously developed to exploit the flat floor regulations for maximum expansion, like the multi-element devices seen on top of diffuser exits, are taken away.

The new rules also constrain the area ratio in which to expand the air to keep the wake in a narrower field. All teams appear to have developed their diffusers to the maximum expansion potential here, with no apparent differentiation between cars.



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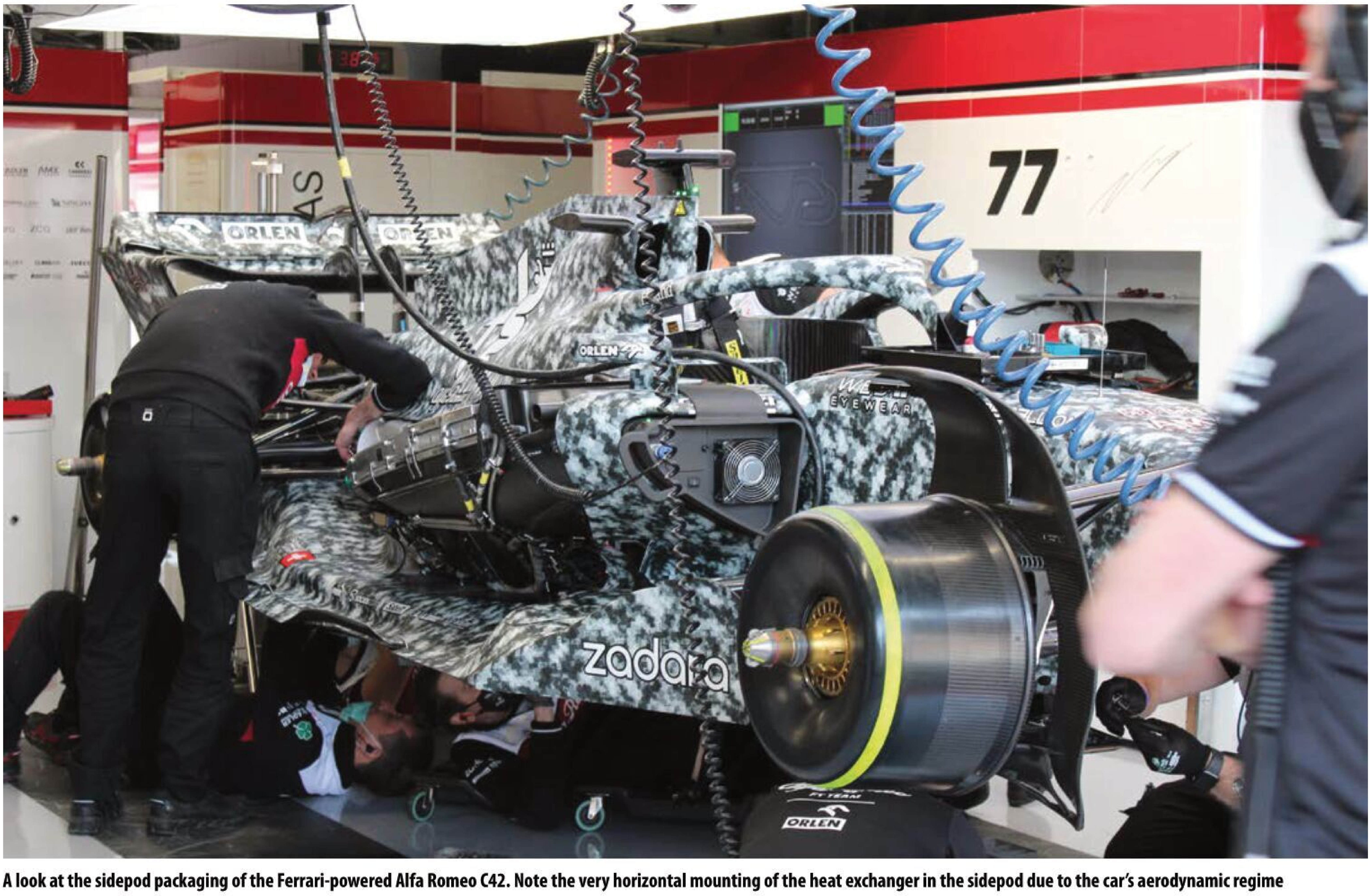
Mercedes investigating the flow viz after a run during the Barcelona test week. Note the backed off inner section to the front wing elements and the significant lateral step between the sections attached to the nose and the main plane



Stewart Mitchell

A look at the sidepod packaging of the Ferrari-powered Alfa Romeo C42. Note the very horizontal mounting of the heat exchanger in the sidepod due to the car's aerodynamic regime

However, teams may implement small fences under the floor post-venturi within the 2022 regulation framework. These produce the same effect as primary fences as they all act on the same fundamental principles – that air passing over them starts to turn and rotate as a function of the pressure delta on either side, and that increases the energy of the airflow.

These micro-scale, post-venturi floor fences could easily be seen on the Alpine A522 (pictured) and, although they were not easy to highlight on other cars, other teams are likely exploiting this area, too.

Front wings

The 2022 Formula 1 front wings are another major departure from the previous generation. Their stipulated design criteria now see the wing elements attached to the nose, thereby abolishing the element-free 250mm wide section on the Y-axis of the wing, known as the Y250. Teams are not allowed any more than four front wing elements on either side of the nose, and the wing must blend into the end plate within a tolerance of a prescribed radius.

There appears to be massive disparity throughout the paddock about how best to load the front wing

The regulations also mandate front wings be swept back from the nose to the end plates at a prescribed angle. The end plate then blends into the front wing elements using a curved profile designed within a radius tolerance.

The pressure delta a swept-back wing creates over a given surface area is less than a wing perpendicular to the flow, but it can deal with a higher flow speed before reaching compressibility.

When the primary surface aerodynamic regime is compared to previous generation cars, the 2022 front wings' contribution to overall car downforce is decreased. However, the wings are critical in different ways now, namely the flow field conditioning they produce, thanks to the introduction of the under-floor tunnels.

A few teams, such as McLaren, Alpine and Aston Martin, have opted to detach the lowest front wing element to control and condition tunnel flow and run the front wings high to support their tunnel flow field strategy. Others, like Mercedes and Ferrari, have an attached lower element that blends into the nose like the rest of the structures.

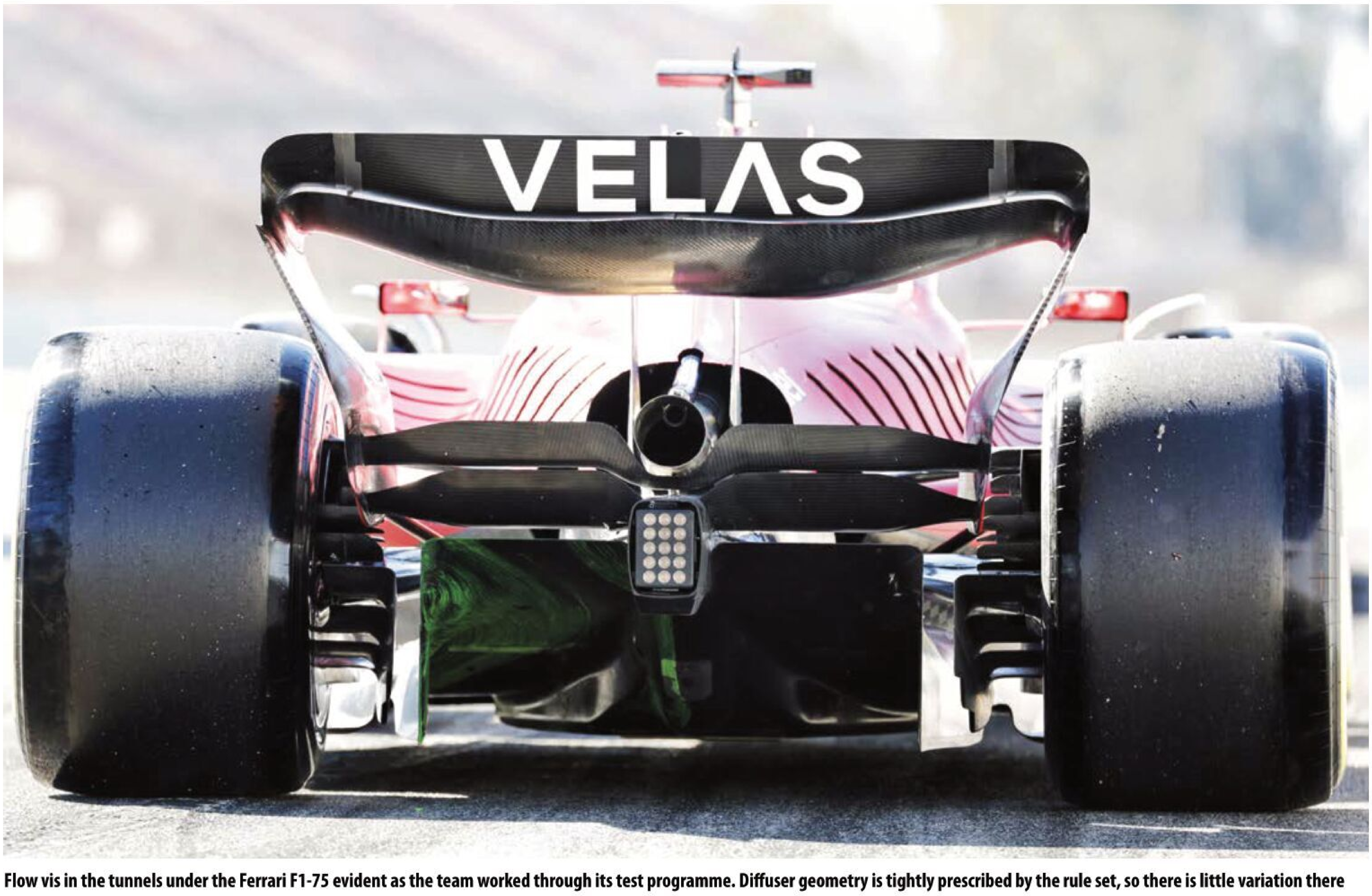
There appears to be massive disparity throughout the paddock about how best to load the front wing. Ferrari and Haas have opted for a very flat profile from the nose to tip, while Mercedes and Red Bull have a significant arch to the profile in the centre of the elements. Mercedes has a particularly backed off inner section to the W13's front wing elements, with a significant step laterally between the sections attached to the nose and the main planes. Only the RB18 seems to follow this centrally-loaded philosophy.

Rear wings

The prescribed area of the rear wing design focuses on the tips, which coincide with the shape and size of the car's rearward wake. The profile pulls the flow field inwards and upwards with the most aggressive section in the centre and then tapering off at the edges. The new rules force the flow to roll off the top of the wing tips, rather than generating tip vortices that narrow the expansion of the dirty air coming off the back of the car. Again, there is no significant disparity between the cars here as this area is prescribed.

The profile attempts to alter the span load across the wing to deal with wing tip vortices, moving the wake upwards. The wing is therefore much shallower towards the edges where that wing tip vortex sheds. This smooth transition down the wing takes energy out of the vortex and sheds it in the most efficient way possible.

The way a wing curves also helps reduce stress concentrations on the end plates, potentially making for a stiffer and lighter solution compared to previous generations.



Flow vis in the tunnels under the Ferrari F1-75 evident as the team worked through its test programme. Diffuser geometry is tightly prescribed by the rule set, so there is little variation there

Stewart Mitchell

Ferrari's sidepod and Coke panel bodywork features deep sculpting on its upper surface. It also exploits the new louvre regulations to reject excess heat from underneath the body panels

Despite the constraints, there is scope for development and some very different main plane profiles were noted across the grid, coinciding with the cars' design philosophies and how the main plane is fed. The Alpine A522, for example, features a very shallow profile to the centre of the main beam, which extends out wide to the wing tips, while the AlphaTauri AT03 has a deep central profile.

Additionally, the beam wing, which sits atop the gearbox, is quite open in terms of the regulations and consequently yielded many interpretations. This area has clearly provided a lot of development focus for the teams trying to achieve an efficient solution to integrating the flow coming out from the diffuser with that coming off the beam wing – it brings the tunnel stream together with the main wing one in an up-washing system.

The beam wing's traditional job is to reduce pressure at the exit of the diffuser, giving the diffuser less pressure delta to recover. Designing an efficient beam wing element can therefore recover the flow field to low negative pressure, allowing the floor to operate more efficiently.

Some teams have developed multiple-element beam wings stacked on top of the diffuser exit, while others have a single, more aggressively profiled element. At Barcelona testing, Red Bull's RB18 featured the most extreme single element beam wing, while most teams opted for a two-element beam wing design. It has yet to be seen whether or not this design will be retained for the season.

This is just the start of a long road of development for these new racecars

Bodywork

Shaping the so-called Coke panel ahead of that beam wing is critical, as teams want to feed it the cleanest airflow possible. The more the bodywork is designed to work the beam wing harder, the more aggressive the floor can be, leading to a potential reduction in rear wing, thereby reducing drag.

Around the Coke panel is where the body generates adverse pressure going into the car's rear. This is more pronounced on some 2022 cars than others, and depends primarily on how the teams want to exploit the floor regulations.

McLaren's MCL36 sees a very high upper Coke panel exit, with the sculpting of the car's tail primarily around the floor. Most of the other teams, however, have shallow and relatively closed rear bodywork, exploiting louvres in the sidepod and engine cover bodywork for cooling.

There are already a number of different interpretations of the rules, and this is just the start of a long road of development for these new racecars.

View from the trackside

At the end of the second day, it was already clear that porpoising was a major feature during the first running of the new cars. First glimpse of the new generation cars on track clearly showed that the teams need to spend time setting up the cars to control this phenomenon. There is not long for them to do so as the second test is mid-March, one week before the opening round.

At vmax at the end of the straight in Barcelona, 300m from the corner, and therefore 150m from the braking zone, I watched as the cars visibly struggled to maintain a stable aero balance, with the floor hitting the ground. Additionally it appears at first glance to make a difference whether or not the DRS is open.

Teams were running different strategies, with some going for race set up and others qualifying runs, and entry speed to the corner obviously affects the level of bouncing that the cars were experiencing.

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Go with the 'flow

How Alteryx, a data automation and workflow platform, is helping McLaren Racing find, manipulate and exploit data in Formula 1 to run more efficiently

By STEWART MITCHELL

Performance is a multi-faceted word in Formula 1. It can be associated with lap time, driveability, top speed, tyre degradation, downforce, power unit output and efficiency, overall reliability, component stiffness, aerodynamic drag, resource efficiency in cost, time, energy and much more.

The various areas of performance can all influence each other, so measuring depends on the data collected and the type of analysis undertaken. Each Formula 1 car carries around 300 sensors, which collectively produce 1.5 terabytes of data throughout a race weekend. For a race season, a two-car team produces some 11.8 billion data points. These must all be filtered and analysed to look for performance gains, reliability issues or strategies to make better decisions for the team. Or to work out what their competitors are doing.

From the 11.8 billion data points, it is fair to say that teams reasonably understand what the car is doing. However, to make performance gains and other improvements, they need to keep developing the car, find ways to be more efficient, and understand the car's characteristics in ever more detail. This is where the virtual world and the physical world intersect.

When engineers design parts for the car, teams produce them virtually in CAD, so there is an exact digital twin of each full-scale car in CAD, and a fluid dynamics model.

Teams will simulate the properties of any new element in this digital world before a component is built, tested and put on a car.

CFD analysis produces a further vast amount of data, measuring every cubic centimetre of airflow around the car in high resolution. Post-CFD analysis is then equally critical, as it influences the decision on whether a part should be taken to the 3D printer and manufactured at 60 per cent scale for testing in the wind tunnel.

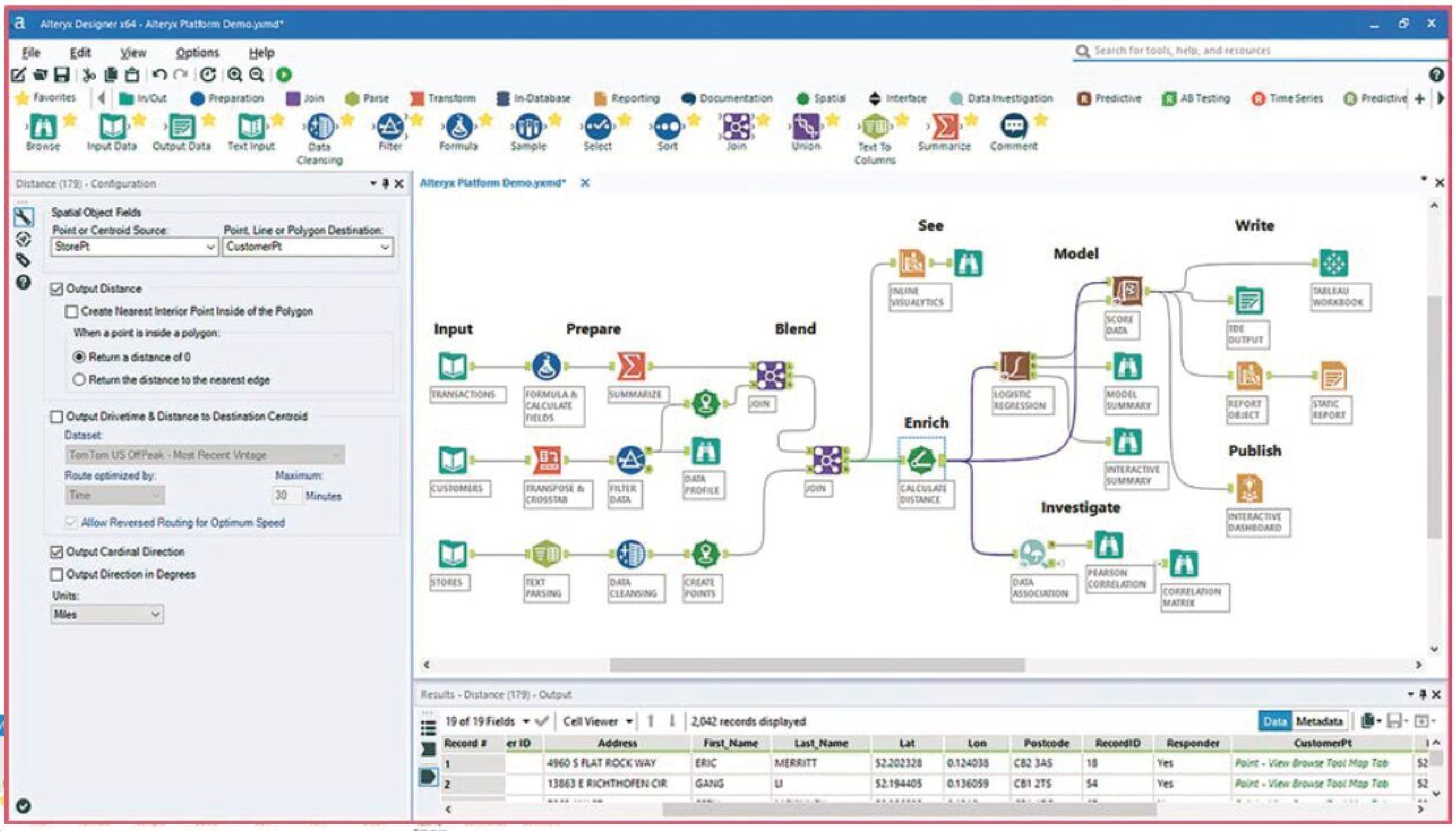
The wind tunnel then has a series of physical sensors that produce around a terabyte of data each time the tunnel runs.

'The IT team here at McLaren is a lean group, but our role is to ensure we provide platforms, technology and tools that the various teams within the Formula 1 group need to be as efficient as possible'

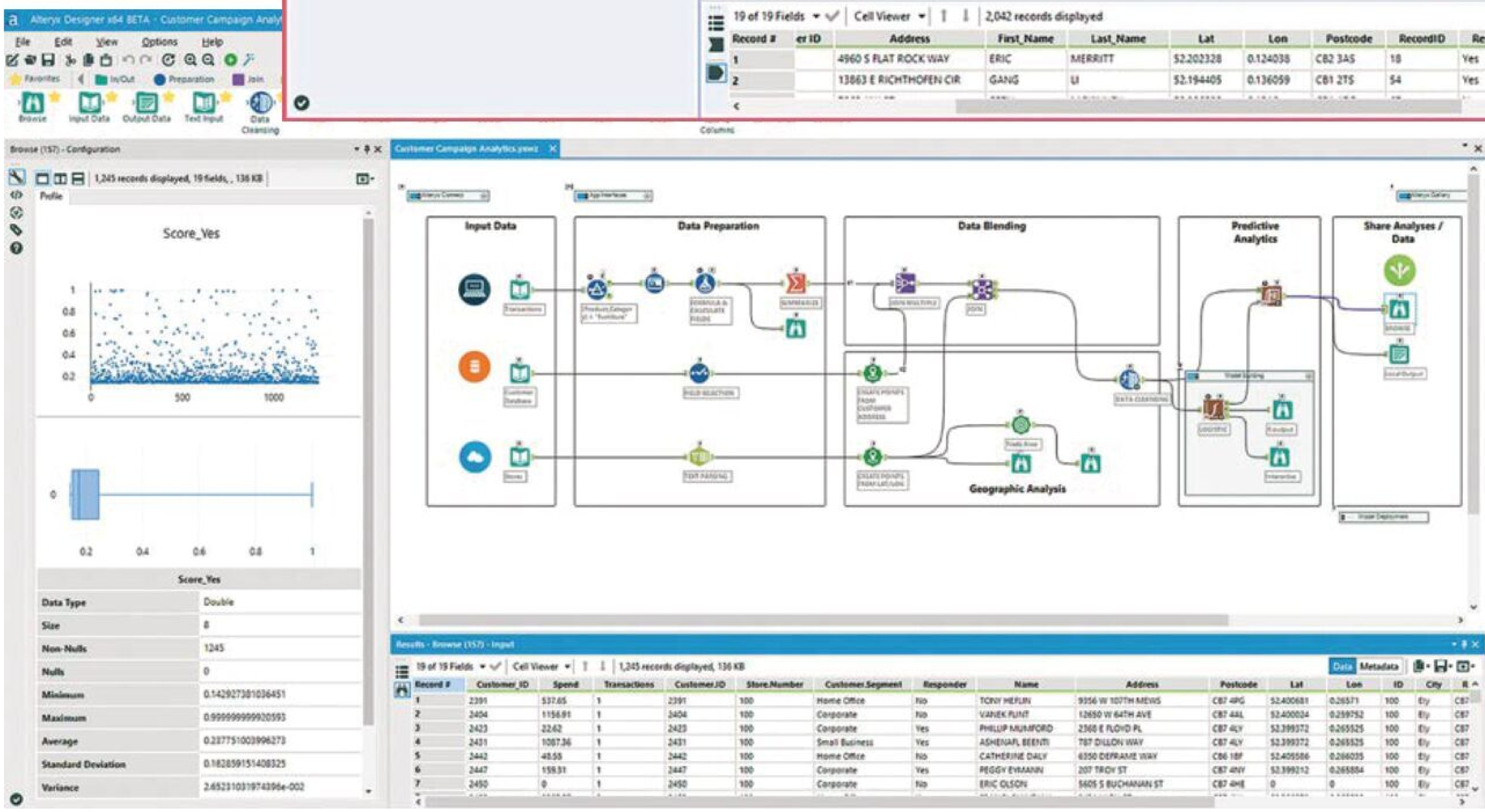
Edward Green, head of commercial technology at McLaren

Photos: Alteryx

Lando Norris in his McLaren MCL35M at the 2021 Italian GP



Alteryx Designer showing typical workflow steps for developing operations, a function used extensively in Formula 1



Collaboration functions of various data sets on the Alteryx platform

From here, engineers must decide whether to take a part to full scale, considering the resource cost, lead time and production expense. If all those criteria are met, the part must then be manufactured and tested on the car with the 300 sensors onboard on a Friday afternoon for two practice sessions of an hour each, and once more on Saturday morning before qualifying and the race.

With resource restrictions now written into the regulations, teams can't just add a new part to the car every weekend and analyse the differences on track. Several elements are brought to the car each time there is an upgrade, which makes understanding the performance from any one part very challenging.

With the three primary data systems (CFD, wind tunnel and track) each very different, the challenge is to correlate the data further up the chain.

If the part(s) brought to the car yield a performance improvement, engineers want to go through the data and make sure the performance gains found on track match the predicted performance seen in the CFD and wind tunnel data. If the correlation is there, they have better confidence up the chain and are more informed when deciding whether to take the new parts further into the process.

Each Formula 1 car carries around 300 sensors, which collectively produce 1.5 terabytes of data throughout a race weekend

Data management

Edward Green is head of commercial technology at McLaren, and is responsible for the IT within the team and all of the sub-teams that work within it that collect, analyse and decide what to do with this colossal amount of data.

'The IT team here at McLaren is a lean group, but our role is to ensure we provide platforms, technology and tools that the various teams within the Formula 1 group need to be as efficient as possible. We put capabilities into our team that all can use.

'With the various data sets coming together, somehow you must converge them and contrast them against one another. That's quite a complicated process to manage, and several stakeholders want to see the data in different forms and different ways.

'We use software called Alteryx, a data automation platform, to bring multiple sets of data sources together and look at them pre- and post-race analysis, as well as back office operational data.

'Its real strength is consolidating and correlating data sets, and allowing different sub-teams to manipulate and model what they want with the outcomes. Additionally, we want to make sure it's in a workbook and a workflow that multiple people can go into and create different paths and explore data in different ways. That's what Alteryx is allowing us to do.'

When data is collected, engineers create a model from it. The type of model depends on what they want to achieve. They might, for example, choose to do some predictive analysis, or cut and slice particular segments of the data set they are investigating as they see fit. There are tens, if not hundreds, of people involved in that process, and each sub-team wants to make sure it's working as efficient as it possibly can.

'If we focus on the cost of car build and workflow programming, working under resource-restricted regulations is quite a complex data challenge,' notes Green.

Of course, performance on track is ultimately where the development needs to prevail, and the correct data needs to be used, in the right way, for any changes made to the car to translate into lap time improvement on track.

The CFD and wind tunnel tools predict what the upgrades might do in terms of speed and lap time in different conditions, but that only matters if engineers can exploit those predictions on track.

Cost implications

Formula 1 now implements a cost cap for each team of £145 million ($175m), which has wide-ranging implications on resource management, affecting every element of the sport.

Even just understanding the cost of a Formula 1 car is a highly complex job.

'Manufacturing, engineering and finance have all now been bought together through Alteryx'

Edward Green, head of commercial technology at McLaren

There are multiple suppliers and the correct scheduling of parts is vital for bringing any upgrades to the circuit at the right time. The pace of that scheduling alone can affect the cost of a component, especially when you realise that around 80 per cent of an F1 car will be brand new between seasons and pre-season testing, even within a relatively stable regulation set.

Within that, as many as 20 different data sources are telling the engineering team what is on the car on a given race weekend, and each one contains the finance and background information for all those different parts.

Someone must bring together and analyse all those data sources to understand the actual cost of a particular car spec at any given race. Currently, many teams do this manually, but that relies heavily on learnt and absorbed knowledge, and independent widgets used by various departments to put all that data into an acceptable state to report back on the cost of the car, and the potential price of the next one.

'This was one of the first applications of the Alteryx system for McLaren Racing: to figure out the real cost of the car and all the resources required,' highlights Green.

With the cost cap in place, the back-end offices of Formula 1 teams must now be as efficient as their engineering counterparts to ensure the right resource spend on each element of the car.

'Manufacturing, engineering and finance have all now been bought together through Alteryx,' continues Green, 'which can bring together the different data sources and manipulate them into the various states they need to be in to start correlating them, and subsequently work out the real cost of the car.

'The information churned out from Alteryx is then used to inform

'We are starting to see some efficiencies on the back end from our financing and procurement procedures because they're able to see and understand the data better'

Edward Green, head of commercial technology at McLaren

design and development techniques, manufacturing processes and to make sure there is minimal wastage by guessing when we should produce parts.

'We are starting to see some efficiencies on the back end from our financing and procurement procedures because they're able to see and understand the data better, whereas before we held it in different tool sets and systems.

'With the big regulation changes in 2022, Alteryx has allowed the team to manage the transition between 2021 and 2022 efficiently.'

The IT capabilities within a Formula 1 team are vast, with software that enables engineers to make informed decisions regarding things like material usage in a specific component. Perhaps there's a trade-off between using a particular carbon fibre lay-up design for an element and cost.

There are already software packages in use for manufacturing that highlight different techniques such as machining, 3D printing and pre-preg carbon fibre to ensure the part is manufactured in the most efficient manner. The software will therefore assist the designer in choosing the most effective solution in terms of time, energy and money expended.

'These software packages expose insights much faster than we had before,' confirms Green. 'We are starting to see their impact in the manufacturing lines in deciding how to produce long lead time items. When is the right time to make those, and whether we in source or outsource production.'

Race analysis

McLaren also uses Alteryx for pre- and post-race analysis, as Green explains: 'When the cars return to the garage, we offload all the data onto server and storage infrastructure in the garage. We have two 38U cabinets' worth of compute that we take with us to every race and that links back to Mission Control over a private internet connection back at the McLaren Technology Centre.

Alteryx software is used for data science and analysis within the whole of McLaren F1. It is designed to make information accessible to any data worker with drag-and-drop data prep, data blending and analytics functions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'We then have other data sources, such as points from weather or GPS, that we're also tracking throughout the race weekend, and those will be archived and put into the appropriate place for analysis once we get back from a race.

'Post-race analysis goes on for two to three days, and then attention will turn to preparation ahead of the next one.'

During that post-race analysis period, the team must efficiently select what is helpful from all the amassed data, and decide what they can address, and what might be beneficial to investigate (or not) when they go to the following circuit.

The debrief sessions also take on board driver feedback and consider if performance at the race itself matched pre-race expectations, and identify any anomalies the team want to look into from the performance side.

'Alteryx is the final piece of the puzzle between the data that comes off the car and how it relates to the simulation. You get your telemetry data and data from the simulator, pick on the correlation points that we're keen on and build out the model from there.

'The data we capture will be classified to match, so the sensors on the car will be compared with sensors on the simulator and correlated.

'Part of the post-race analysis is getting the drivers back in the simulator to check the correlation with what came off the car at the circuit. This plays into some pre-race work too, as many circuits have corners with similar characteristics. We can therefore profile corners throughout the season and group their characteristics together, and then use that to model our performance development for a series of circuits.

'We make sure we give the team everything they need, and for our partners and for us get every bit of understanding we can to and from the cars.

'We will also do a post-race analysis of other teams and how they worked on the weekend to understand whether they would have made the same decision,' adds Green.

Formula 1 teams are constantly developing their IT operations and systems to enable them to meet current demands and future challenges. And with 2022 having 23 races on the calendar, that's a major undertaking.

IT in Formula 1 is just as complex and fast moving as any other part of the team, but… can make the difference between knowing precisely what the car is doing and simply hoping for the best

Throughout all of it, the IT teams must ensure that not only is all the software and hardware working, but that they're not missing any vital data, not running above capacity and that maintenance is not having any significant impact on the race season.

Yes, IT in Formula 1 is just as complex and fast moving as any other part of the team, but through choosing and working with the best partners, it can make the difference between knowing precisely what the car is doing and simply hoping for the best.

Lando Norris leaves the garage at the 2021 Italian Grand Prix with his MCL35M adorned with a livery highlighting McLaren's data science and analytics partner, US-based Alteryx Analytics

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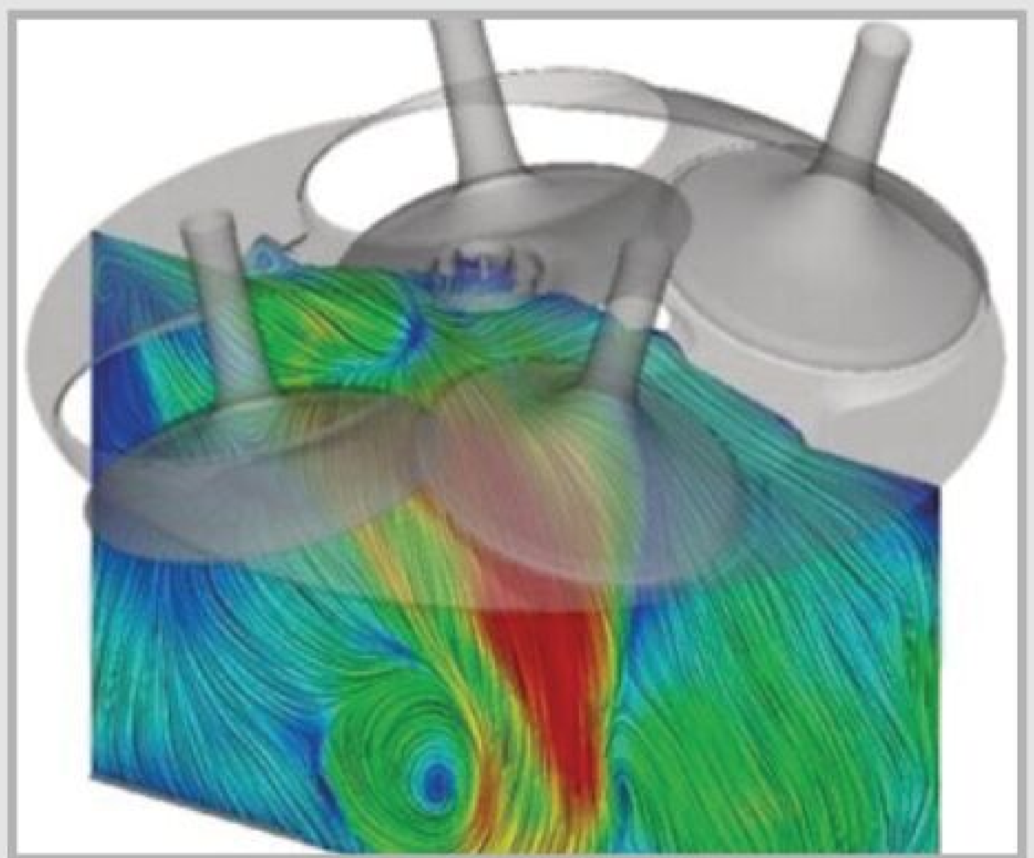

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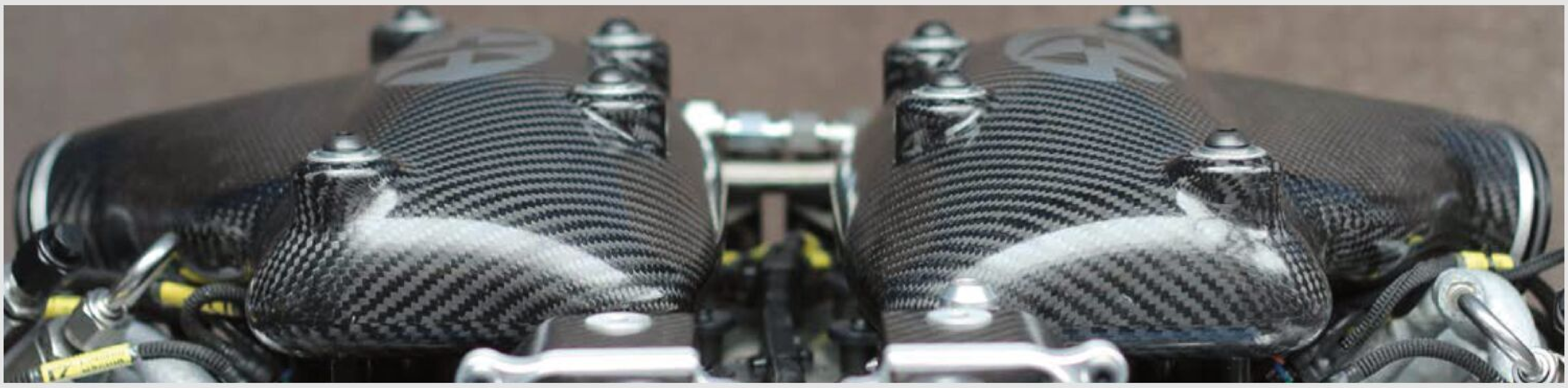

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Loss adjusters

A team of engineers and scientists are monitoring the chemicals in racing drivers' sweat, with the aim of improving their health, and making the car faster in the process

By ANDREW COTTON

There are two organic elements to a racecar that can directly affect performance and which, particularly in endurance racing, need to be replaced regularly. One is the tyres, which degrade and ultimately cost performance, or risk failure. The other is the driver, who similarly degrades over time behind the wheel, and runs a real risk of crashing.

While much is known and studied about the tyres, and indeed the car is set up to extract the maximum from them before they expire, very little has been published about driver performance, particularly in long-distance races.

A team of scientists and engineers were recruited by IMSA's Wayne Taylor Racing (WTR) lead engineer, Brian Pillar, as part of a new Driver Science programme in a bid to better understand what a driver goes through behind the wheel in order to improve performance. The Driver Science team have begun a study that it hopes will make the car faster, more reliable and safer, by paying more attention to the component behind the wheel.

One of the most interesting parts of the relationship is that one of the drivers in the WTR team, Ricky Taylor, has a younger brother, Jordan, who also races in the IMSA series professionally, and both have taken part in the study. They share very similar approaches to life and racing, which makes the scientific comparisons between them both valid and interesting.

Very little has been published about driver performance, particularly in long-distance races

WTR is a multiple champion team, and has found success in major races, particularly the Daytona 24 Hours. It races in the IMSA WeatherTech Sportscar series, which features a combination of race lengths ranging from 100 minutes to 24 hours. The team competes with an Acura DPi, one based on an ORECA LMP2 chassis, but fitted with a 3.5-litre turbocharged engine, Xtrac gearbox and runs on Michelin commercial race tyres.

Health plan

The team has been involved with the scientists for a few years now, monitoring its drivers in all areas, including inside the car during a driving stint. Wearing patented patches and harnesses, the study team has been able to monitor such as fluid loss through sweat, blood flow, muscle and cognitive wellbeing, to gain an insight into the overall health of the team's drivers as they complete their stints.

The target for the Driver Science team is to provide live updates to the pit wall in order that the team is able to extract maximum performance out of its team of drivers at any point during the race. The team, meanwhile, is hoping to ensure its drivers are fit and ready to drive at all times, allowing them to better make strategic decisions.

What the programme is trying to achieve is to have a driver who performs at their optimal level for the entire duration of their stint behind the wheel, and recovers quickly enough that they can do so multiple times.

Key to the study is a revolutionary new patch that gathers data on the driver through their sweat. The patch monitors

WTR driver Ricky Taylor (right) gives up his data to CoreSyte's Scott Ackerman in the pit at Daytona via a patch on his arm. One target is to eventually provide live data to the pit wall

The ultimate goal of the programme is to have a driver who performs at their optimal level for the entire duration of their stint behind the wheel, and recovers quickly enough that they can do so multiple times

such as electrolyte, sodium and potassium loss from the body, and is capable of transmitting live data back to the team. In this way, the team is hoping to build a performance profile on each of its drivers.

Using this data, the team is working with ORECA to develop a new drink system provided by company, FluidLogic, in the homologated chassis. FluidLogic has a pump that can deliver a substance of different viscosity to water, which would allow the team to deliver driver-specific drinks developed by its partner, Hammer Nutrition, which has been a presence in the endurance racing market for many years.

However, if ORECA does not homologate the system, the Driver Science team plans to apply to have the new LMDh regulations make it a team decision to run it.

The data is being shared with a team led by Dr David Ferguson, with the aim of publishing studies in driver wellbeing, an area of motorsport that has been woefully lacking, compared to other sports such as soccer and American football.

Much is known about the fitness requirements for athletes competing in other sports, but very little research has been done looking into the ultimate performance requirements of what the Driver Science team calls 'Driver Athletes'.

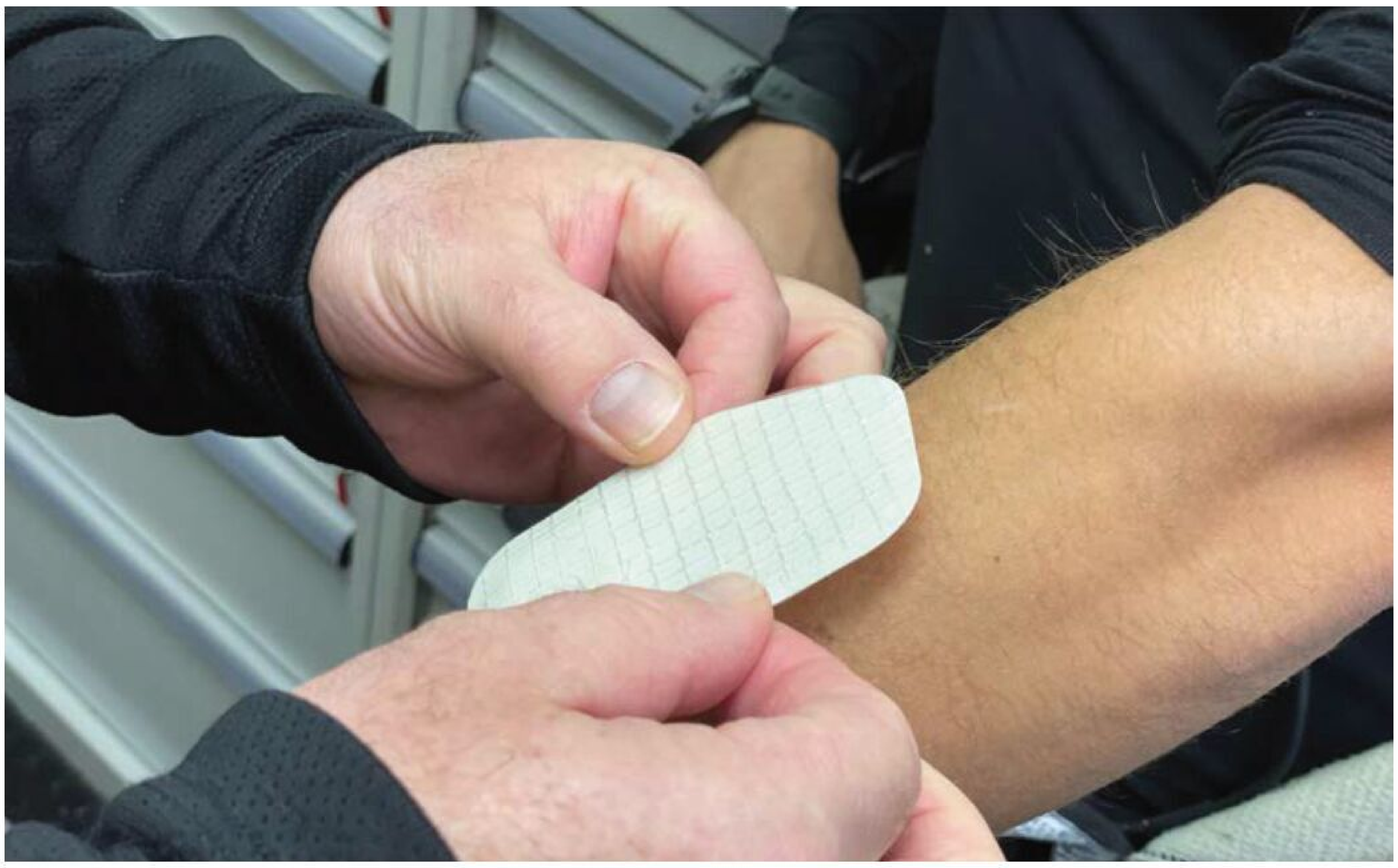
Peak fitness

Achieving peak physical fitness is a measure that varies depending on the sport, and within motor racing from discipline to discipline. An endurance racing driver in a Prototype, for example, will be subjected to different demands compared to a Formula 1 driver who pilots a faster, higher downforce machine for a maximum of 120 minutes. An endurance racing driver can be required to drive a car for up to 240 minutes, and repeat the cycle multiple times within a 24-hour period.

There are many parameters at which to look. What stresses does a driver's body undergo in the cockpit? How are they affected by different weather conditions? How does a different configuration of circuit affect how a driver performs through a stint behind the wheel? How much body fat should an endurance driver ideally carry? What should a driver drink and eat in preparation for a weekend to provide maximum performance behind the wheel, and the fastest recovery time out of the car? What exercises can a driver do, both physically and mentally, in preparation for a race weekend? And what tools can be used on board to maintain a driver during a mammoth stint, other than feeding them water?

Pillar was the first to notice that there was something missing from his knowledge base when he took part in a seminar organised by sponsor, Konica Minolta, and attended by several doctors. Questions were asked about the stresses his drivers encountered during an endurance race, and he didn't know the answers.

Within the team he set up the Driver Science division in 2016, and since then has been looking at ways of generating data through experts in the field.



CoreSyte

Key to the study is the CoreSyte patch, worn on the driver's arm, which monitors electrolyte, sodium and potassium loss from the body

CoreSyte

The patch will ultimately transmit its data back to the pit so the team are able to make assessments of driver health and wellbeing, which could impact pit and stint strategies. By knowing what and how much a driver is losing allows the team to customise their fluid intake

'Typically, around two-to-three per cent dehydration leads to performance loss. The reaction times then change, and you start to see things like elevated heart rate'

Scott Ackerman, founder of CoreSyte

Richard Dole

Driver fatigue is an issue at all levels of racing, but none more so than endurance series, where drivers at races like the Rolex 24 at Daytona are expected to complete long stints at peak performance through day and night sessions

CoreSyte

The patch takes a sweat sample every three minutes, giving a string of data points throughout a race that can then be analysed

CoreSyte

Even after a strenuous race, drivers are still expected to operate at their peak, even if it's just for interviews and autograph sessions

The team linked with Australian company, Wireless Motorsports, to find a way of transmitting driver data back to the team, but it was a chance meeting at a driver autograph session with Scott Ackerman, founder of CoreSyte, that gave the team the method of collecting the data they needed with a patch stuck to a driver's forearm.

Cognitive function

'My background is in exercise science, human performance and exercise physiology,' says Ackerman. 'Now with this technology, we got to the point where we say how can we learn about what's happening with elite performers when they are asymptomatic? It doesn't take very much before a driver can start to show degradation in cognitive function, but what does that mean? How do you quantify that? It's very difficult, and we don't necessarily try to do so. What we do know is the medical charts show there are changes, and typically, around two-to-three per cent dehydration leads to performance loss. The reaction times then change, and you start to see things like elevated heart rate.'

For the pit wall to deliver messages to the driver about their wellbeing may seem like a nanny state feature, but drivers vary in their habits, with some hardly drinking, others emptying the bottle. The driver's perception of what they need to maintain performance may not match with reality, and the data gathered allows the team to help with maintaining physical ability for a longer period of time.

'Based upon your sweat profile, we can begin to make recommendations to your training, and we've seen that, with a few of our drivers, once they learn more about what's already happening in their bodies through this data patch, they can tune their training accordingly,' continues Ackerman.

'The data patch takes a sample of sweat every three minutes, so we have a long string of data points we can look at after the stint. If the race is hot and humid and we are starting to see that, at the end of the second stint,

What tools can be used on board to maintain a driver during a mammoth stint, other than feeding them water?

'The ultimate dream is how do we build a robot driver that can do that for three hours, recover in two hours, and then get back in and do it all over again'

Brian Pillar, lead engineer at Wayne Taylor Racing

they are already near maximum levels, we want to ultimately be able to give actionable data to the pits in real time to allow a decision to be made on a driver change, for example.'

Working with the Taylor brothers, the team has been able to analyse this data in detail. The study showed Ricky had a higher electrolyte loss, while Jordan leaked more potassium, so the ideal fluid either driver would need during a stint would be different.

'The magic is the ratio metrics between sodium loss and potassium loss,' says Ackerman. 'It's understanding what each driver loses, and our goal is to reach a point where we can give an individualised cocktail, so to speak, to ensure they're replenishing the ideal amount of electrolytes they're losing.'

Hammer time

This is where Hammer Nutrition comes in. The ability to deliver a driver-specific fluid while the car is in motion would help keep a driver sharp behind the wheel for longer, and reduce recovery time out of the cockpit.

Traditionally, driver changes occur either on a pre-planned schedule, or if a driver is struggling for some reason as evidenced in lap time loss, or complaints from the cockpit. The latter is the most important, although probably the least reliable.

'We are pretty honest with each other,' says Pillar. 'Ricky is the best judge of himself, having to be involved in this. We are definitely relying on the individual to report back right now, and I think a big piece of information [we are missing] is fluid loss. Where we are trying to get to is a drink system that can deliver things like electrolytes back into the drivers' body, and integrating their personal data with data from the car so that at some point we have a guide to the driver needing certain things at specific times.'

Gathering the data on the CoreSyte patch involves collecting sweat in separate layers of the patch and then using sensors to communicate with the car's central system to deliver the results back to the team.

CoreSyte

These two sodium profiles taken at Petit Le Mans (left) and at Daytona (right) show how fluid loss differs between races. It also differs greatly between individual drivers, so there is no one-size-fits-all solution

'There are tonnes of sensors on the car, and that data is coming from it to the pit, so we need very little extra data to make this work,' says the CoreSyte team's technical lead, John Chiochetti. 'What I am focused on is collecting as many of those sensor inputs as possible in time synchronisation while the driver is in the car, marrying their data with car data, and turning all of that back to the team in the pit.

'We have all the environmental data, conditions in the car, impacts and *g* forces. All of those stresses, so we can take that data, put it together with the sweat profile, the electrolyte content losses for a particular athlete and put all of it into a data science platform that allows us to build profiles.'

Robot driver

'We want to have a qualifying driver for three hours and reach the point where, through nutrition and training, the driver can do three hours of qualifying laps,' says Pillar. 'The ultimate dream is how do we build a robot driver that can do that for three hours, recover in two hours, and then get back in and do it all over again.'

With the data gathered, the next stage is to turn that into something that improves the overall health of the driver. To do that, the team has linked with Dr Ferguson from the Department of Kinesiology at Michigan State University, to help them develop a thesis-based analysis into driver performance.

Dr Ferguson has worked with NASCAR, IndyCar and endurance racing drivers to establish some fitness indicators: 'If we take endurance racing drivers, competing at Daytona or at Le Mans, they need to have a very high aerobic capacity,' he says. 'In order to be an elite endurance driver, they need to have a VO2 max number – the maximum amount of oxygen you can consume – in the region of 60-70ml per kg of body weight per minute. That's roughly the same as a semi-pro cyclist or runner. Their body fat needs to be between 13 and 16 per cent, which seems high as other pro athletes are around three per cent, but this is where motor racing is unique.

'The length of time that they are competing, 24 hours, 12 hours or whatever the race distance, coupled with their travel and training schedule, requires them to have some level of fat so they have fuel to actually do the work they are required to do.

'The last thing the drivers need is to have a certain threshold for isometric neck strength, and that really depends on the type of car they are going to drive.'

Prototypes and high-downforce cars are clearly going to require more neck strength than something like a GT or Touring Car.

Strain index

With a picture of what physical and mental state a driver needs to be in order to drive at a high level for long periods of time, attention then turned towards maintaining that within a racecar. Using a physiological strain index (PSI) from one to 10, the team can work out what strain the body is under. PSI is nothing new, it was developed more than 20 years ago and is based on a combination of core body temperature and elevated heart rate compared to resting.

However, applying that to a racing driver in real-time competition could prove valuable.

'We know that once you reach a value of six, fatigue is setting in and performance can be compromised,' says Dr Ferguson. 'When you reach a value of eight, you are in trouble. You are not only having fatigue and performance loss, you're also probably at risk of a heat injury or illness, so that's the primary marker we go towards.'

Using the systems outlined here, the team can monitor sweat loss and then advise their driver on when to be drinking. And can judge that against overall car performance.

'You should have about 10 per cent of blood going to your brain, and the rest towards the skeletal muscle,' says Dr Ferguson. 'Even though you are sitting there in the car, your muscles are working and they need oxygen to do their job. We know high *g* forces alter that so, during times of high *g*, you will shift blood away from your head and actually direct it more towards your abdomen. But it doesn't do any good there. What will happen then is you start to scavenge blood that's not going to your brain. The driver doesn't know that you are not getting blood flow to your brain, but your decisions become compromised, your reaction time reduces and that could lead to a corner apex being missed, a wheel dropped on the dirt or, worst case scenario, the car flying off the track and crashing.'

Maximum effort

Clearly, then, a driver's health degrading has an effect on the car, and how it is being used.

'The skeletal muscle does not have sensory nerves, so you think you're giving maximum effort, but you don't know you're not,' says Ferguson. 'Typically, when a driver is going to the brakes, there is a sharp increase in brake pressure and then a bleeding off modulation effect. That's optimal, but when the driver is dehydrated or fatiguing, the brake pressure is slower to increase. Then, once they have reached peak brake pressure, they can't modulate it because the muscle has become impaired. They think they are modulating the brake pedal but they are basically taking their foot off the pedal. This can lead to understeer, can tear up the tyres a little more and then the driver will report back to the pits that the tyres are going away, or that the brakes are fading.'

Interestingly, the team has not allowed Dr Ferguson and his team to look at the mechanical areas of the car. He notes with a wry smile the story of LMP1 teams being required to run an air conditioning unit in their car, and Toyota using that to cool its battery rather than its drivers.

One of the ways of maintaining a driver's health is to ensure they take on the right amount and type of fluid. Currently, this can only be done before the driver gets into the car, but WTR is hoping ORECA will allow a different kind of pump that enables them to replace the necessary fluids for each driver. In the past, different fluids have burned out the pumps allowed in the category, and an incomplete delivery of fluid can lead to build up in the tubes, ultimately causing blockages.

> **'We know that once you reach a [PSI] value of six, fatigue is setting in and performance can be compromised. When you reach a value of eight, you are in trouble'**
>
> *Dr David Ferguson, Department of Kinesiology at Michigan State University*

At the PRI Show in Indianapolis in December, the team reacquainted itself with FluidLogic, having first met in 2018 when the company's technology was very new. The introduction of the IndyCar Aeroscreen, and the effect that would have on the driver by reducing airflow around the cockpit area, accelerated FluidLogic's development, and now the Driver Science team is looking to take it a step further, with three bottles that deliver the right mix of fluids to the driver during a triple stint.

'We said, why couldn't we make a change every time we do a pit stop and have the recipe of the liquid change,' says Ferguson. 'The second bottle could be characterised with what the driver needs, and the third hour could be different again. Right now, we can't influence that.'

It's potentially a big study within the endurance racing community, but it could expand to other areas of the sport, and indeed other sports, as the quest for the perfect athlete continues.

Ageing effect

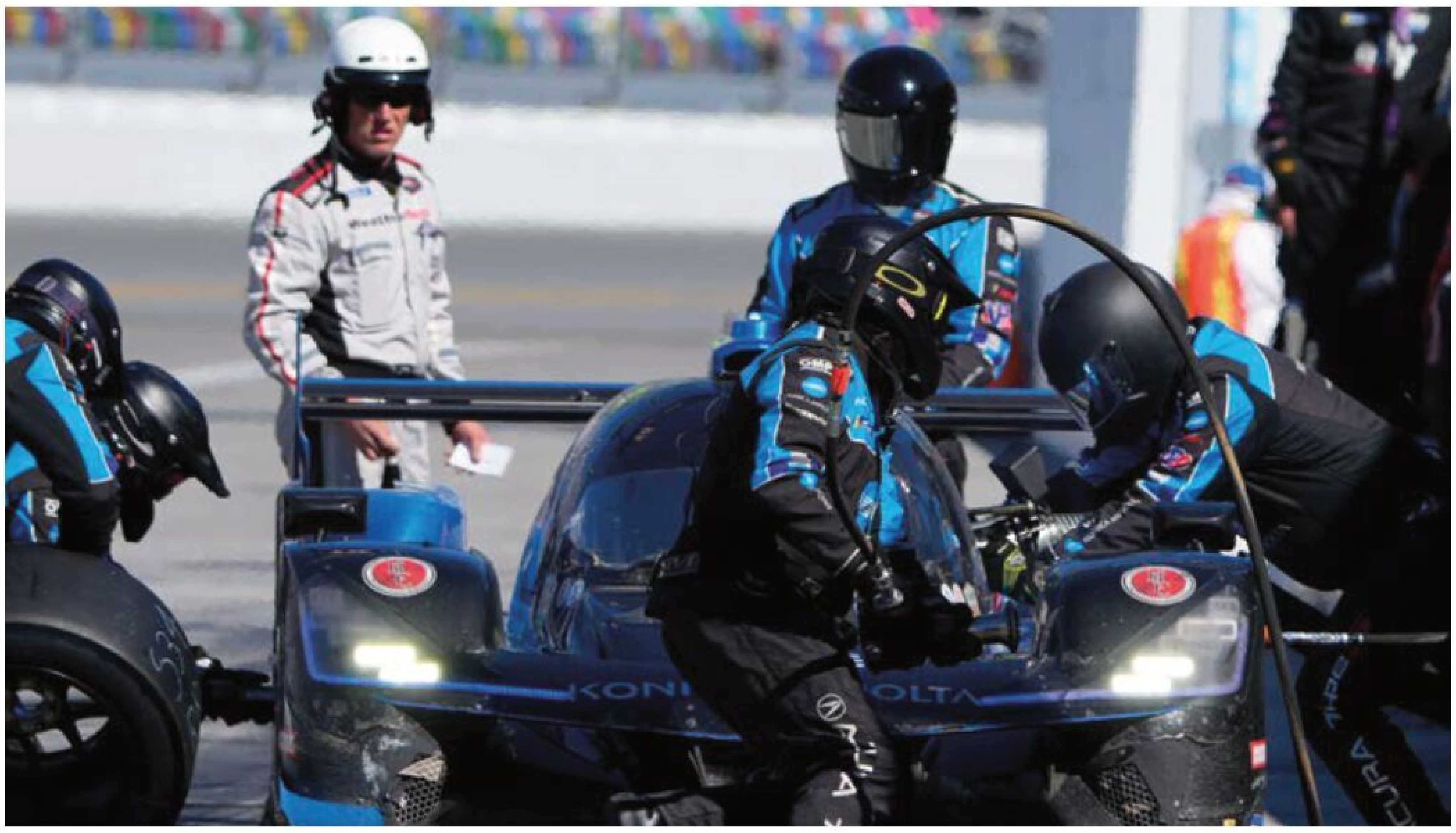
It is well known that Sportscar drivers can race longer through their careers, which commonly is put down to a lower level of downforce, and therefore less requirement for physical strength. However, there is more to the phenomenon than that.

While endurance racing has been trying for years to move away from the idea that it's an old drivers' home, and looks instead to build a younger driver roster, the ability to continue long into a driver's 40s at the top level can't be denied. Medically speaking, an older driver might rely more on cognitive skills to keep them quick, rather than physical strength, and there are plenty around with the skills needed.

'Let's say there's an infinite number of grey matter neural connections you can have,' says Ferguson. 'If you start to have fewer than that, you have to rely more on your fitness to prevent fatigue. If you are less fit [or older], you probably have more neural connections and cognitive capacity than the other drivers out there.'

Clearly, cognitive function can be improved with training, and drivers are often subjected to exercises similar to those used to treat dementia, or Alzheimers.

'In terms of racing, what we have seen is that as drivers age, they tend to drift towards cars that have a lesser *g* loading on them than maybe they did earlier in their career,' notes Ferguson. 'This comes back to brain blood flow. As you age, everything declines so, if *g* forces reduce brain blood flow, it makes it harder for you to make decisions and make them quickly. You might just drift towards cars that don't elicit the *g* forces, or maybe the cars are slower than what you are used to. That's what we think is going on, but it's really hard to quantifiably test that.'


Richard Dole

Driver perception of what their bodies require to maintain performance differs greatly, and the ultimate aim of this programme is to monitor fluid loss and then provide drivers with custom-mix drinks that replace the exact electrolytes they are losing while racing

Michael L Levitt

’Vette bill

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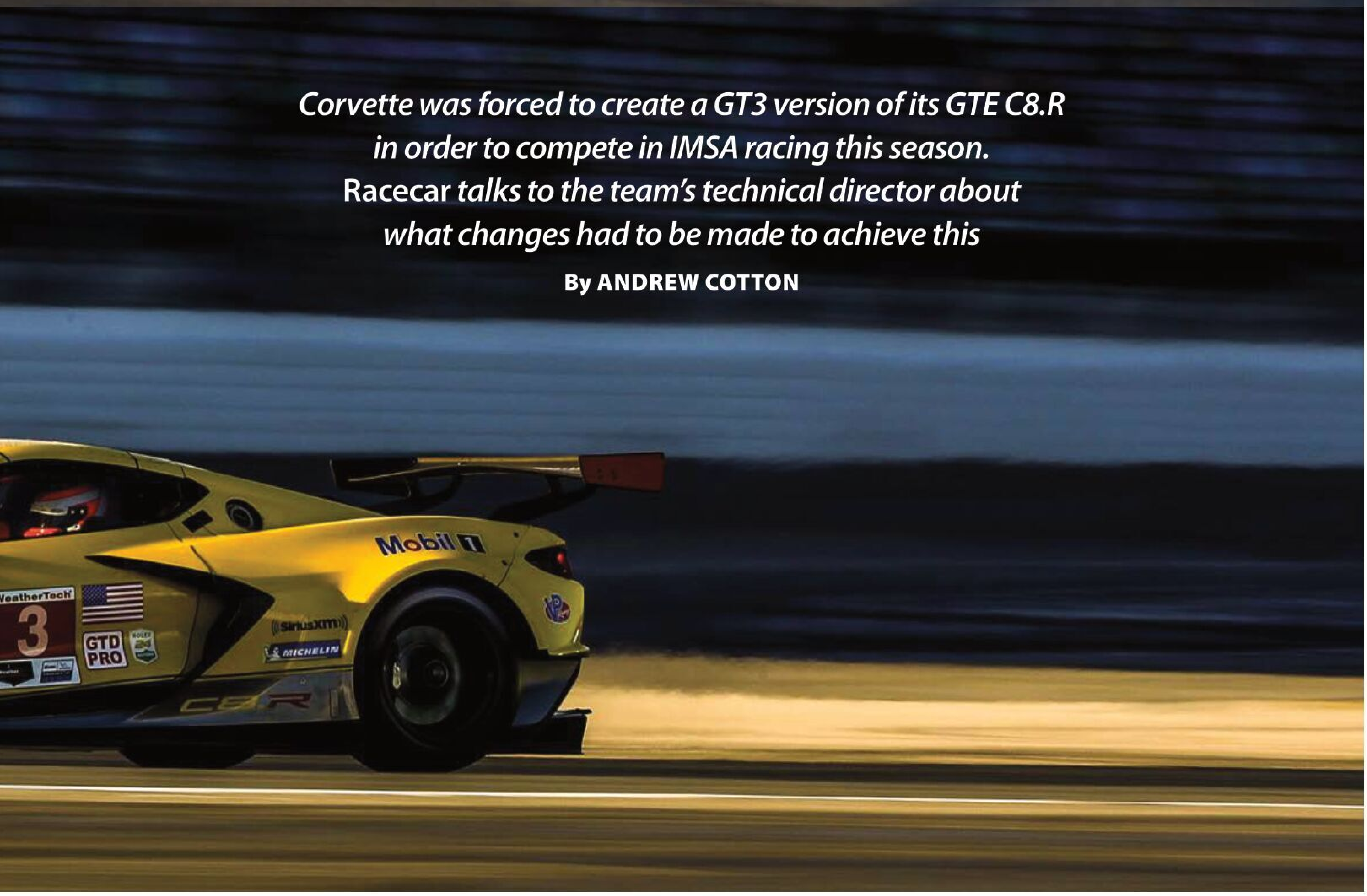

Corvette was forced to create a GT3 version of its GTE C8.R in order to compete in IMSA racing this season. Racecar *talks to the team's technical director about what changes had to be made to achieve this*

By ANDREW COTTON

GT racing has taken its next step into the future with the introduction of the GTD Pro category into the IMSA WeatherTech Sportscar series this year. The category allows professional teams and drivers to compete in GT3 cars, and it replaces the GTLM class, which was for the immensely popular GTE cars in the US.

The GTD Pro class ran for the first time at the Daytona 24 Hours at the end of January, and it was contested by no fewer than eight manufacturers, including four who were involved in the now-defunct GTLM category. It helped that each of the manufacturers already had GT3 versions of their cars running in customer hands. All, that is, except Corvette.

Once the announcement was made that GTLM was finishing in the IMSA series at the end of the 2021 season, Corvette made some key decisions. It will continue to race the GTE version of the car in the World Endurance Championship throughout 2022, but needed a programme to continue racing in IMSA for the next two years. The LMDh decision went to Cadillac, with a global programme including IMSA and the WEC, so that wasn't an option, and Corvette wanted to continue racing the C8.R in GT competition.

Delayed decision

It therefore chose to covert its GTE car to GT3 specification for IMSA, before the introduction of the new, ground-up GT3 car in 2024. But even that was a delayed decision. Just prior to Le Mans in 2021, IMSA announced it would not run a different Balance of Performance compared to the GTD class after all, and that the difference between the two would only be that the GTD Pro category could include all professional drivers. Corvette did not want to compete against its customers but, as it has none for the new GT3-spec C8.R anyway, went ahead with the conversion.

There was nothing simple about changing the C8.R from GTE to GT3 specification. While the body is similar, and Corvette Racing had tested the ABS braking system in competition already, the fuel, power levels, downforce levels, weight and differential regulations are all different. There was also the small matter of changing from Michelin's confidential tyre used in GTLM to the commercial tyre, which has a further knock-on effect on performance.

GM worked with IMSA to bring the C8.R into the right performance windows and the two agreed where compromises would need to be made in order to ensure the conversion would make sense from a cost and performance perspective.

Once all the parameters were agreed, performance balancing had to take place. At Daytona it was immediately clear that was still a work in progress, as IMSA made adjustments to the C8.R throughout the week leading up to the race. Although Corvette was not forthcoming with its own assessment of the BoP system, it was clear the 'Vettes were struggling for overall pace. Their average of best 20 per cent laps under green compared to the Risi Ferrari 488 were eight tenths of a second per lap slower.

Although the GTE and GT3 regulations were designed that a body could be built to suit both categories, and Ferrari was the first to do that with its 488, the detail needed a lot more thought and engineering work.

Moveable ballast

The first fundamental change to the C8.R was an increase in weight of 65kg, compared to the comparison weight of the GTLM-spec car at Daytona in 2021. However, it wasn't quite as simple as just adding to the existing weight carried, as GT3 cars by regulation carry ballast boxes in the cockpit, while the GTLM cars are able to spread their ballast to strategic points around the car to help improve performance.

Corvette Racing/Richard Prince

Corvette maintained as much of the GTLM car as possible, including the chassis, engine and suspension. Cockpit was unchanged

Corvette Racing/Richard Prince

On top of the extra weight, IMSA's BoP department added a further 15kg prior to the Daytona race, and a reduced rear wing angle

GTE and GT3 regulations were designed that a body could be built to suit both categories [but] the detail needed a lot more thought and engineering work


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The next big headache was going from Michelin's confidential-spec tyre to the commerical-spec one used by the rest of the competitors in the class.

Corvette Racing/Richard Prince

Fitting the ballast into the cockpit meant the team had to reconfigure the entire passenger compartment, and that included moving the air conditioning unit, fire bottle, battery box and other electronics.

'It was like a game of Tetris to get it all in there,' said Corvette's technical director, Ben Johnson. 'Ultimately it's about transparency. Everyone knows where the weight is, and how much is in there in GTLM, and you can homologate the best places around the car to put the weight. But now it's all mandated in one spot. Moving the battery, fire bottle and so on, none of those things you can just move. All the wiring harnesses change, you are putting bushings on the floor, so it's much more difficult than just sliding them around and clipping them back down.'

With the changes obviously came a different weight distribution that then had to be accommodated in the set-up of the car. 'You then have to understand what that does to the front and rear weight distribution, the overall c of g height, and then how you tune that,' continues Johnson. 'That has a negative impact on the balance on the tyres, so then you have to tune that, too.'

The team did a lot of testing in simulation, and it seems to have worked. According to them, the balance hasn't changed since they put the new configuration onto the car and set it down to run, which was something of a relief to the programme engineers.

Corvette Racing/Richard Prince

The Corvette Racing team had tested the ABS braking system in competition knowing that it would be required under GTD Pro regs

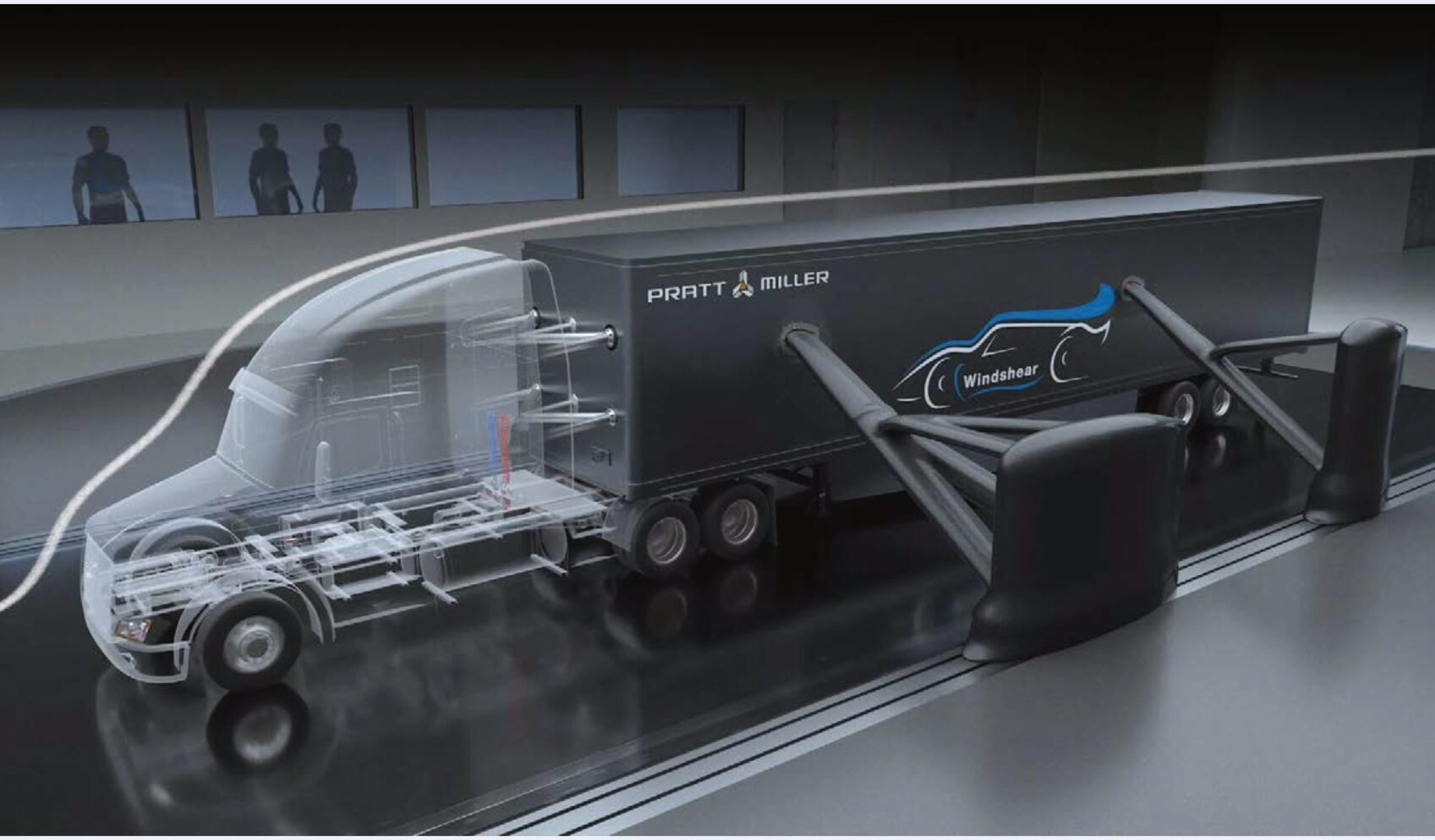
One of the change items that could not be simulated easily was the move away from the confidential Michelin tyre.

Rubber headache

Using the same rubber as everyone else, which include front, mid and rear-engine layouts, has been a headache for all involved, including tyre supplier, Michelin. Daytona threw up an additional parameter in that overnight air temperatures

'You lose so much with going to the commercial tyre from the confidential one, particularly under braking'

Ben Johnson, technical director at Corvette Racing



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704-788-9463 INFO@WINDSHEARINC.COM WINDSHEARINC.COM dropped to just above freezing, and track temperatures fared little better, falling just below 40degF (4.4degC).

Wild pre-race predictions of ice forming on the track were highly unlikely and predictably never happened, but the extreme temperatures did have an effect on car handling in all classes, and on tyre management.

'If it was going to be 85-degree track temperatures to the end of the race we would be more concerned about degradation,' confirms Johnson. 'You lose so much with going to the commercial tyre from the confidential one, particularly under braking.'

The hotter races might throw up more degradation for the Corvette than other GT3 competitors, but how much is not yet known.

'We did enough track testing that we are comfortable on how to operate this tyre, but the mass of the car is way out of line with the rest of the class,' says Johnson. 'It's not like we're in a unique situation compared to the rest of the class, but the car is heavier than the GTLM configuration [we have run for two years].'

Aero changes

Aerodynamically, there were very few changes needed as actually the GTLM regulations are more restrictive than those for GT3. However, IMSA mandated the team has two wing configurations, according to whichever circuit it will run the car this season. At Daytona, the team had to run a higher rear wing than it had on the GTLM-spec car, but that had only a small effect on the overall performance. 'There's no changes to the overall aero package of the car, it's relatively close to the GT3 windows,' confirms Johnson. 'There wasn't a component change that needed to happen.

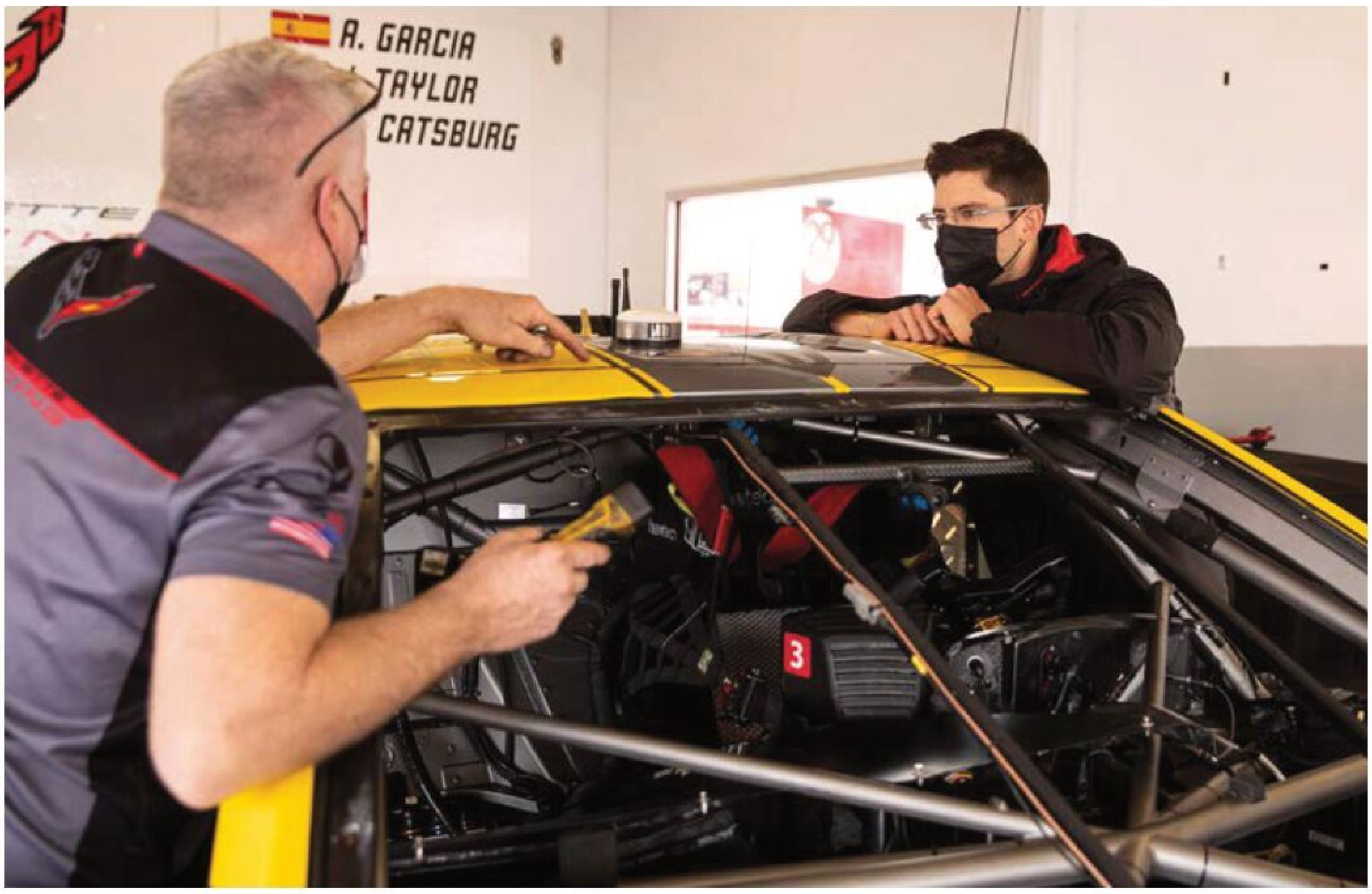
'We had run at a very high drag level, which comes as there is more downforce, but for Daytona we run much higher than we have ever run before. Both the rake angle and the wing angle have increased, and so you have to re-balance it overall. That's simple maths to do, though, and we have all the tools. We got to where we started here, with 11 degrees of rear wing, and you re-balance that with rake and go through the whole process. The actual move to adjust to that higher downforce level isn't too hard, but it has a pretty big impact in terms of how you make up lap time.'

Prior to the race, the BoP department added 15kg to the base weight of the car, and balanced that with a reduced wing angle to help with top speeds on the banking.

The rear diffuser was also not changed as, again, the GT3 aero is more open than GTLM. Under GT3 regulations, the diffuser can start at the leading edge of the rear tyre, while the GTLM regulations started from the rear axle line, meaning a shorter tunnel and therefore a disadvantage in similar guise.

One of the biggest changes under the skin came with the gearbox and differential. The GT3 regulations allow for fewer choice of gear sets – three, instead of four – so the Pratt and Miller team had to work on that, while leaving the casing the same.

The change in diff' was a bigger effort altogether, as the team had to lose some of the tuning options available on the GTLM car. 'The GT3 rules only allow a ramp and preload differential,' explains Johnson. 'The Salisbury diff' is what it would be called under GTLM rules, where they [the set up options] were more open. We had to



Corvette Racing/Richard Prince

Jordan Taylor (right) was one of three drivers in the number 3 Corvette. The car was slow in race conditions compared to Ferrari

Corvette Racing/Richard Prince

Shifting weight meant moving the air conditioning unit, fire bottle, battery box, plus all their wiring, and other electronic items

'The actual move to adjust to that higher downforce level isn't too hard, but it has a pretty big impact in terms of how you make up lap time'

Ben Johnson

remove anything that wasn't allowed by GT3 regulation and it's a balance tuning item you don't have any more. It's not a major impact, but it's something we had to update the notebook on and see how it related, how the differential package now works with the new tyre, and then you have to go back through and re-set everything.'

Power down

One of the key performance changes was the power output from the engine. Smaller air restrictors, down nearly 1.7mm from GTLM spec, reduced power significantly, but meant the team could run the same production-based engine. The organising body allowed the team to continue with sonic restrictors that have been used in GTLM, instead of switching them to the FIA GT3 air restrictor, in order to reduce the cost of converting the car.

The organising body also fixed the lambda, consistent with other GT3 cars, while in GTLM it was more of an open mixture, with only the richest mixture being limited. Switching from the E20 fuel used in GTLM to the VP100 fuel was another detail change the team had to accommodate in order to compete this season.

'Engine regulations are more open in GT3 than they are in GT,' argues Johnson. 'Because of the customer focus of the GT3 car, their engines tend to be lower cost and you take some compromises in how you design the car because it's in customer hands. Those pressures aren't the same if you have a factory-only car. There's less compromise but, ultimately, the way the rules are written it's not significantly different.'

The car also ran with torque sensors, the only car on the grid to do so, in order to help the BoP team accurately judge power output. Despite running the engine exhaustively on the dyno to perfect the BoP under GTLM rules, they still needed to be sure they had the changes right in order to prevent other GTD manufacturers having cause to complain.

One advantage the reduction in power realised was that the cooling package was plenty for the new specification, something the engine team was delighted about.

'I haven't been able to make any changes to the cooling because the engine is going to be working slightly differently, at a slightly lower power level. So, ultimately, you are just over-cooled at this point compared to what you were,' confirms Johnson.

'GT cars are always on the ragged edge of cooling to make sure you are maximising the aero, so the engine guys are a little happier now that we have tonnes of overhead.'

Even the electronics are similar between the two classes of cars, although again the cheaper option would be selected had this been a customer-only programme.

The team plans to run the updated car for two years in IMSA, where it is welcome, but in the meantime will work to produce a customer version of the C8.R for GT3 rules.

'We are going to take all the learnings and everything that has made this car as successful as it has been to win the last two championships [but] take the cost out of them and make them simpler'

Ben Johnson

By regulation, the team has to produce and sell 20 cars into competition within the first two years, which means it needs to set a moderate price point for the car, and then service them both at home in the US and abroad where customers will run them.

'We are going to take everything that has made this car as successful as it has been to win the last two championships, and bring that forward, but you just have to take some of the cost out and make them simpler,' says Johnson. 'It has to be a turnkey car that people can just go and race.'

For now, though, they have to run the cars in IMSA competition for two years before they can introduce the ground-up re-design of Corvette GT competition car.

Outwardly, the GTE and GT3 Corvettes may look similar but with different fuel, power level, downforce, weight, differential type and tyres, that's where the similarity ends

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Compare and contrast

An analysis of the performance balance between 2WD and 4WD Hypercars, using the first season's available data as the basis for the study

By ANDREA QUINTARELLI

The 2021 FIA World Endurance Championship saw the debut of the Hypercar class, comprising a two-wheel-drive car built by Jim Glickenhaus' team and a four-wheel-drive hybrid from Toyota. In 2023, LMDh cars will also be eligible to race in the WEC, and in the American IMSA series, with a two-wheel-drive hybrid. It therefore makes sense to look at the available data from 2021, and make a comparison between the two very different configurations.

After a season of racing, both the understanding of the rules and the lap time simulation tool the author coded and used to analyse LMH cars performance has improved significantly and this, together with the data collected during 2021, enables a much better understanding of the real state of play in this new class.

Key parameters

With the tyres being supplied solely by Michelin, who should ensure level performance between their rubber for different cars, there are four other crucial parameters that influence how LMH vehicles perform:

- Overall traction power
- Mass
- Aerodynamics
- Powertrain architecture (hybrid or traditional)

The first two points are tightly regulated and are factors the FIA and ACO constantly monitor and use to balance the cars' performance.

In terms of powertrain, the rules mandate the power window each car must be able to produce, providing power curves the engine designers must stick to. The window of maximum power is between 480 and 520kW, plus three per cent tolerance. The regulators monitor cars' compliance to the rules using driveshaft-mounted torque sensors.

During the first season, Toyota and Glickenhaus were given different weights and powers, to try and bring them closer together in terms of pace. This was also done to compensate for the Toyota having an electric motor pulling the front wheels and, according to the rule set, being all-wheel drive above 120km/h (with a dry track). At Le Mans, the Toyota had a minimum weight of 1066kg and a maximum power of 515kW, while the Glickenhaus ran with 1030kg and 520kW.

The overall target referred to an aerodynamic efficiency (lift-to-drag ratio, or L/D) of about four, although *Racecar*

understands that the final target mandated by the class regulations was slightly higher than this.

Downforce and drag

This is only a part of the story though. The teams are also given a window in terms of maximum and minimum downforce and drag their cars can produce, with the possibility to vary aerodynamic properties by adjusting only one single aerodynamic device (the rear wing, for example).

Racecar's understanding is that the minimum downforce is set at a value of 4.05 for the aerodynamic downforce coefficient multiplied by the frontal area (CzA). The maximum allowed value for the same coefficient should be 4.25.

Beside this, each car's aero map was populated by measurement tests performed in the Sauber wind tunnel. Basing on the obtained aero map, the regulations stipulate how to calculate the values of downforce and drag coefficients than need to be compared to the target figures.

The appendix of the regulations dealing in detail with the aerodynamics of LMH cars is not publicly available. Last year, *Racecar Engineering* assumed that, to be compared to the targets, the complete map needed to be averaged, with each point (combination of front and rear ride heights, roll angle and yaw angle) being given a different weight.

Latest insights reveal this to be true for downforce, but not for drag. While for downforce the weights each point has could still make a sensible difference on the final average value that will be calculated and compared to the targets, for a directional study like the one presented in this article, one would probably not go far wrong by simply averaging the aero map on a window of ride heights representative of the cars' working window on track.

For drag, in terms of compliance with the regulations, the significant part of the map (again, combination of front and rear ride heights) is one representing end-of-straight (high-speed) conditions. In such scenarios, cars normally run at low ride heights because of the high downforce experienced. The rules mandate the drag value be checked against the rules and give a minimum measurement at four different combination of low front and rear ride heights.

In absence of better data, in our last article about the LMH class the author erroneously assumed that for drag the rules would mandate a weighted average of the aero map, and this influenced partially the results and the conclusions drawn.

While this aspect might seem a tiny detail, it completely changes how manufacturers set their aerodynamic targets in the design and development phases. In particular, with a high-speed circuit like Le Mans in mind, keeping drag as close as possible to the minimum accepted target for any ride height variation becomes very important, because this would lead to higher top speeds and better lap times.

The effects of different aerodynamics characteristics, in particular with respect to ride height sensitivity, is one of the properties that can be easily assessed using lap time simulation.

Tool and vehicle model

The lap time simulator coded by the author is based on a quasi-static approach. Each small section of a track is analysed assuming a constant acceleration and that the vehicle is in stable conditions. The four-wheel vehicle model incorporates full aero maps, suspension kinematics, corner and heave springs and bump stops for each axle, plus anti-roll bars. Powertrain model user inputs include a torque curve, gearbox efficiency, gear ratios, shift time, the portion of driving torque applied to each axle and the minimum speed at which an all-wheel-drive strategy can be activated. That latter point is critical for this study.

Each small section of a track is analysed assuming a constant acceleration and that the vehicle is in stable conditions

The tyre model is similar in structure to a Pacejka model, but with each effect modelled separately, including load, slip, camber and vertical characteristics (vertical stiffness and expansion with speed).

The representative LMH vehicle model has benefited from the data collected during the 2021 WEC season and race results, primarily those related to the BoP adjustments mandated for each track. This study will initially refer to a hybrid LMH car, with the following features:

- Mass of 1161kg (1066kg for the car, as per Toyota's BoP in Le Mans, 75kg for the driver and 20kg of fuel)
- Static weight distribution of 47 per cent on the front axle
- Maximum power at the wheels of 515kW, as per Toyota's BoP in Le Mans (exactly equal to BoP allowed nominal power, no tolerances, nor any other kind of deviation considered)
- Front track width: 1670mm
- Rear track width: 1660mm
- Four 31/71-18 tyres with the same characteristics
- Aerodynamic efficiency (meant as the ratio between downforce map average value and the regulations-mandated, 'end-of-straight'-representative drag point of the map) slightly above four
- Minimum allowed downforce configuration, to emphasise top speed and low drag
- Average aerodynamic balance on map of about 45.5 per cent
- LMP-like suspension design, based on existing Le Mans Prototype vehicles
- Gearbox with seven forward gears, ratios optimised for Le Mans circuit
- Being representative of an hybrid LMH car, the model will also consider a four-wheel-drive system

Hybrid Le Mans Hypercars employ an electric motor propelling the front wheels with a mandated maximum power of 200kW. The application of torque to all four wheels is only activated only above a speed of 120km/h, as per the regulations. So, for this study, the tool uses a simplified approach, with the distribution of torque between front and rear wheels assumed to be constant and equal to the value that produced the best performance. However, this is surely not the case for existing hybrid LMH vehicles like the Toyota GR010, and consequently this approximation will affect the accuracy of lap times predictions. Also, no limitation to the deployment over a lap because of battery capacity are considered in the simulation runs.

The model described will run on a virtual representation of La Sarthe circuit, generated using data logged on the circuit itself.

Aero map effects

Two different aero maps were tested to assess how a car with a stronger sensitivity to ride heights for the most significant aerodynamic metrics of downforce, drag and aerodynamic balance would perform, compared to another with a lower sensitivity, keeping all other parameters unchanged.

The results are summarised in **Figure 1**.

Aeromap	Lap Time [s]	Top Speed [kph]
High RH Sensitivity	201.965	326.97
Low RH Sensitivity	201.441	328.96

Fig 1: Effects of ride height sensitivity on performance

The gap between the two solutions is about 0.5 seconds in terms of lap time, and about 2km/h in terms of top speed. The pace difference produced by the two configurations is mainly due to straight-line performance and, in general, to the average lower drag that a lower ride height sensitivity offers over a lap, because of how the regulations are written.

While the 'low-sensitivity' aero maps considered may represent an extreme example (being about half as sensible compared to the other map), this simple study still seems to highlight an important design target for manufacturers developing an LMH vehicle to fully exploit the regulations, especially on a high-speed circuit like Le Mans.

This becomes even clearer when looking at **Figure 2**, which shows the results of the two simulation runs. The data relative to an aero map with a higher sensitivity to ride heights are in red, while the black lines refer to the run with a lower sensitivity. From above, the first trace in the plot is the 'compare time', which indicates how much gap exists between the two runs at a certain point on the track (in seconds). The second trace is car's speed, the third rpm and the fourth engaged gear.

It is easy to spot the top speed difference in every straight, where the black speed trace progressively climbed above the red one to finally reach a higher maximum velocity before the next braking point, while the 'compare time' changes with at a stronger rate in those sections of the circuit. This is even more interesting, considering that, in some medium or high-speed corners, the set-up with a higher ride height sensitivity actually produces higher mid-corner speed. For example, at Tertre Rouge, located about the 1870m mark at La Sarthe.

The advantage in terms of drag is sufficient not only to compensate the lower corner exit speed, but also to overcome this by about 2km/h at the end of the straight leading to the first chicane.

Figures 3 and **4** also offer an interesting perspective to these results. **Figure 3** depicts the cars' speed (first trace down from the top), together with the key aerodynamic metrics. The second trace down from the top is the downforce coefficient multiplied by car's frontal area (CzA), the third aerodynamic balance and the fourth drag coefficient (CxA).

This simple study still seems to highlight an important design target for manufacturers developing an LMH vehicle to fully exploit the regulations

In **Figure 2**, the run relative to the aero map with higher ride height sensitivity is in red, the lower sensitivity run in black.

It is immediately clear how the downforce produced by the low sensitivity map varies much less over a lap, reaching lower peak values – for example, during braking phases – but also dropping much less in the following accelerations out of corners.

The same happens to the aerodynamic balance. With respect to this, the two set-ups produce very similar centre of pressure positions on the straights, but not quite at the apex of fast corners such as Tertre Rouge or the Porsche Curves, the latter around the 11,350m mark.

In particular, the higher ride heights sensitive set-up produces a more forward-biased aerodynamic balance at the apex of those fast corners, which helps improve the minimum cornering speed even further. This highlights once more how the advantage in terms of drag at Le Mans can be dominant, enough even to overcome better performance in corners.

Finally, the most important element is the significant difference in terms of drag (the lowest trace in **Figure 3**) when both set-ups conform to the rules. This is surely the main driver for the pretty big difference in terms of lap time.

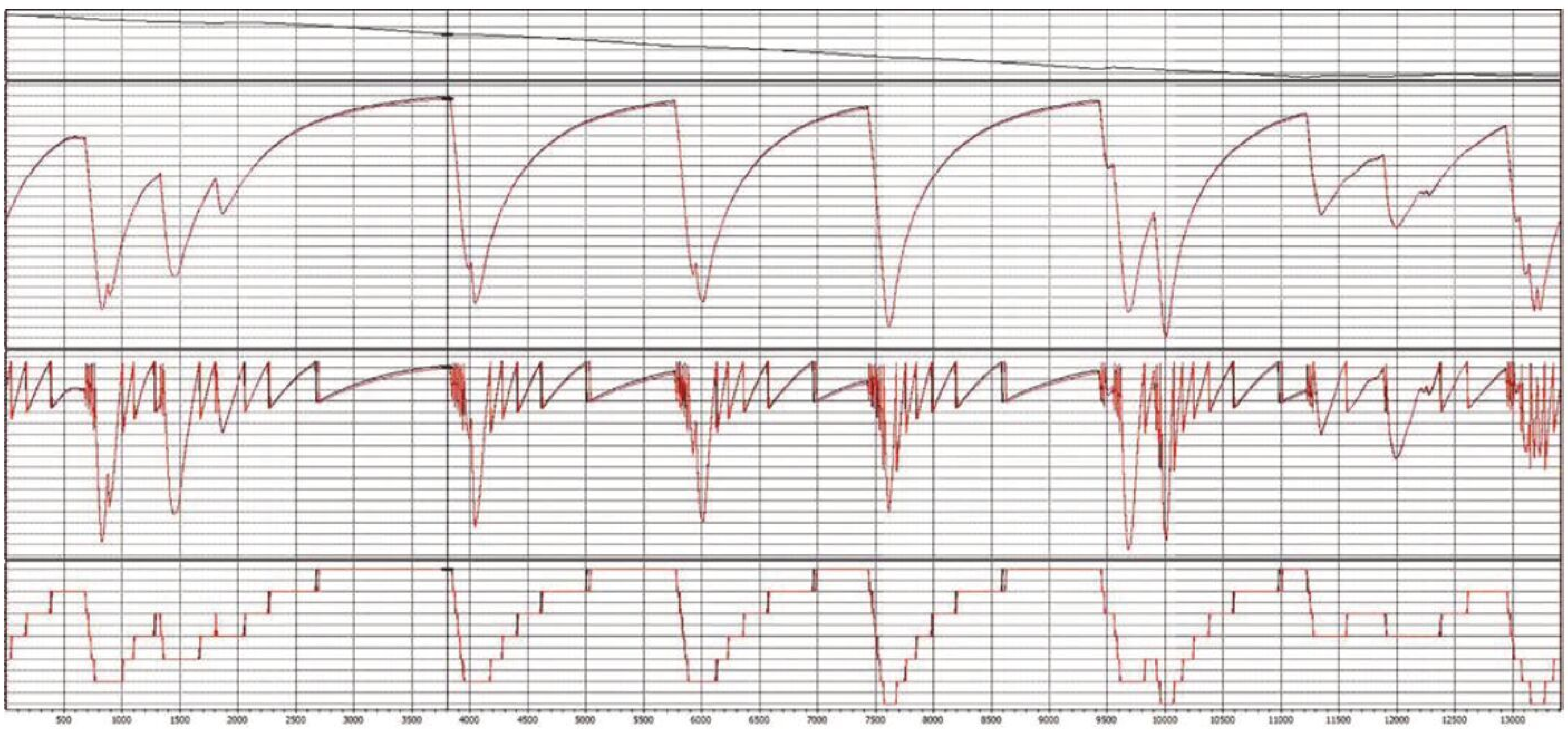


Fig 2: Comparison between the simulation results obtained with an aero map with low sensitivity to ride heights (black), and one with a high sensitivity (red)

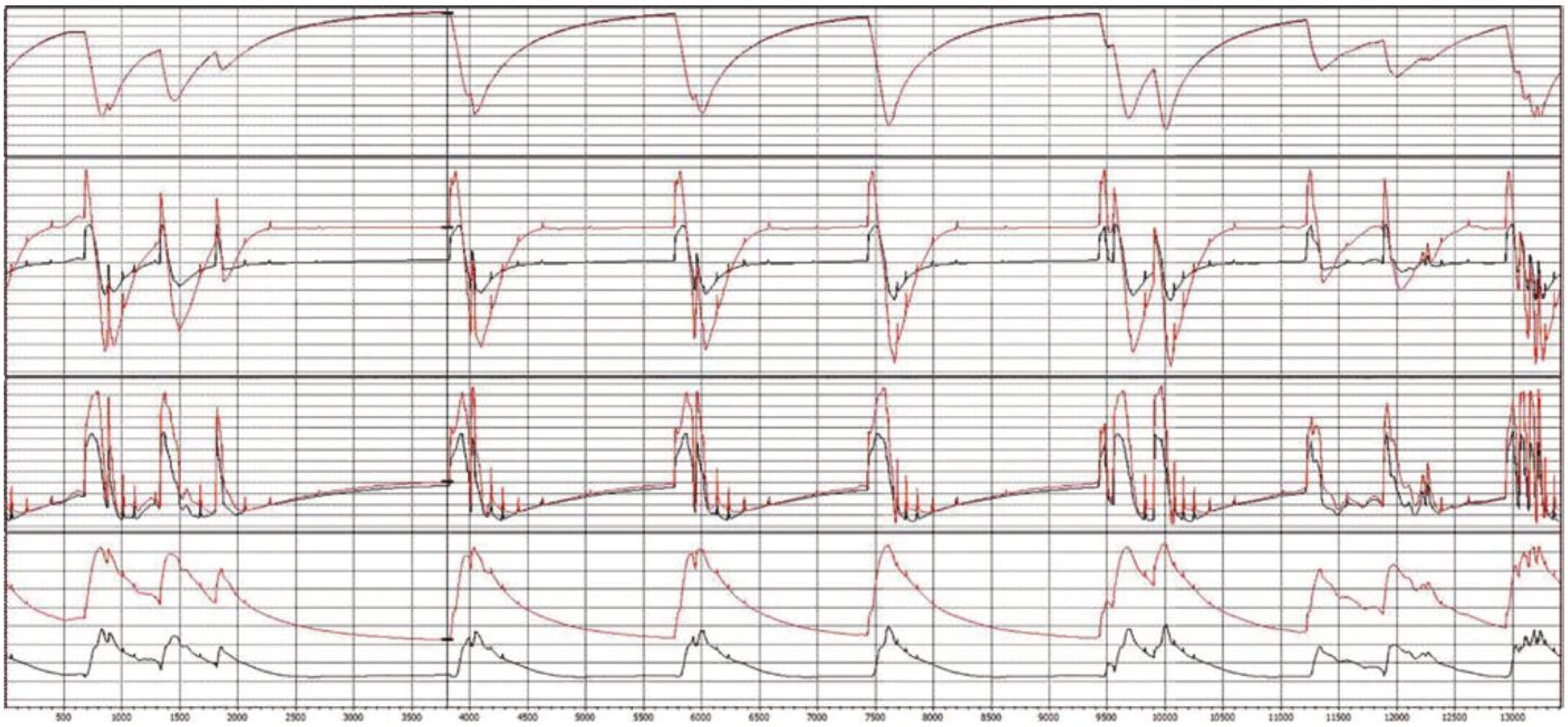


Fig 3: Aerodynamic parameters variation over a lap. Low sensitivity map shown in black, high sensitivity map in red. The traces from the top down are speed, CzA, aerodynamic balance and CxA

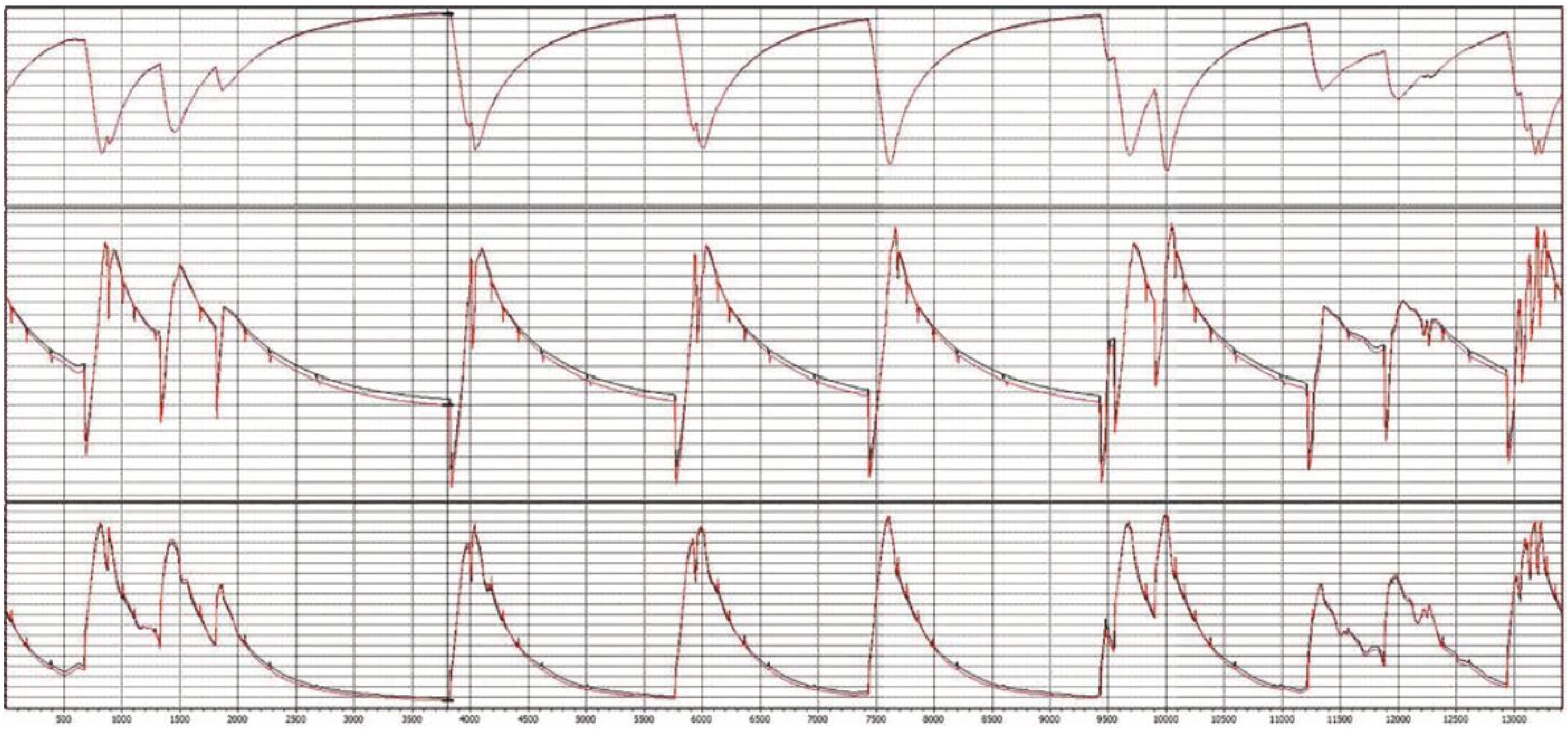


Fig 4: Ride heights variation over a lap at Le Mans. Low sensitivity map shown in black, high sensitivity map in red. The traces from the top down are speed, front ride height and rear ride height

Circuit	Pole Lap Time [s]	Best Top Speed [kph]	Avg Top Speed [kph]
Spa	120.747	307.8	307.8
Monza	95.899	314.9	313.33
Le Mans	203.9	326.8	323.90

Fig 5: 2021 pole position lap times and top speeds (qualifying sessions)

The advantage in terms of drag at Le Mans can be dominant, enough even to overcome better performance in corners

Figure 4 is further confirmation of the effectiveness of a lower ride height sensitivity, within the actual rule set. Again, the red traces are relative to the higher sensitivity set-up, the black lines refer to the lower sensitive one.

The low sensitivity set-up produces pretty much constant higher ride heights over a lap. This is detrimental for performance, as both drag and downforce are worse with higher ride heights. However, the difference between the two laps is small, which confirms the comparison between the two set-ups was 'fair'.

If one aimed for the same dynamic, minimum ride heights over the full lap, the low sensitivity set-up would require lower front and rear static ride heights and this would further improve the lap times obtained with this configuration, making the gap even bigger.

Figure 5 summarises the performance in qualifying sessions of Toyota's no.7 car at different tracks in 2021.

The circuits of La Sarthe, Spa Francorchamps and Monza have been chosen on purpose. Both the Belgian and Italian circuits are high-speed tracks where teams often prepare for the 24 Hours of Le Mans and employ similar set-ups and aerodynamic trim to what they will use for the French race.

Beside the aforementioned assumptions for the vehicle model, a word of caution regarding the powertrain: the FIA / ACO employs torque sensors mounted on the halfshafts to measure cars' actual power and verify their compliance to the rules. Since those signals always have noise, it is likely the teams tune their cars with a certain tolerance margin to avoid being disqualified. This, and the fact that sticking to a given power curve is not a simple task, could suggest the cars' actual power curves could stay below the nominal one.

A quick comparison between **Figures 1** and **2** shows immediately how both actual lap time and top speeds are worse than what simulation produced.

The first conclusion that can be drawn from this rough comparison is that it is probably more realistic to consider the aero map with a higher sensitivity to ride heights for the analysis that will follow. This seems to produce closer top speed to what the Toyota achieved during 2021 qualifying sessions.

Boundary conditions

The next step, then, is to consider the effects of actual ambient conditions in the simulation runs. Air temperature, ambient pressure and humidity all affect air density, and this directly influences the aerodynamic forces produced by the car.

In normal situations, this would have an effect on engine power. However, *Racecar's* understanding is that, while the FIA / ACO mandates a specific correction, calculated with an equation provided in the rulebook, to the nominal, BoP power communicated to the teams, in 2021 this correction was not applied, to further increase the gap between the LMH and the LMP2 classes. In fact, any possible correction related to ambient conditions would have produced a power reduction and, hence, a performance deterioration for the Hypercars. For this reason, only the influence of ambient conditions on aerodynamic forces will be considered in the simulation runs.

The results obtained considering the above factors and the car in minimum downforce trim, are summarised in **Figure 6**. The denomination 'Actual' and 'Theor' indicate actual pole position time and a theoretical lap time, obtained by combining the three best sector times during the session.

What immediately catches attention is the sensible difference between simulation and logged data in terms of top speed. While a simulation will never be exact, especially in this case where the model was built up based only on the regulations and assumptions, the difference in terms of top speed should ring an alarm bell. The manufacturer tolerances mentioned earlier could play a role here, but that alone would not be enough.

In terms of lap times, the relative gap between simulation and logged data becomes interestingly bigger at Monza and Le Mans. Since those races came later in the season, and Toyota had time to develop its car, one would expect them to be closer to 'ideal best' lap times, which is what simulation should provide.

Further assumptions with this model include the car being totally reliable, the driver always following the fastest route and the circuit having elevation, which is not logged from the car.

The only accurate way to judge the correlation, then, is a comparison between simulation results and telemetry data, though that is obviously not possible in this case. Alternatively, some information could be derived from onboard videos, though none of Toyota's available videos show metrics like speed or acceleration.

Trend spotting

The key message is that the simulations presented here need to be used directionally, to isolate trends, without focusing too much on the lap times.

For the next simulation run, the model was set up with the maximum allowed downforce, with both drag and aerodynamic balance were corrected accordingly. Balance, in particular, was moved backward to account for Toyota's only adjustable aerodynamic device being rear wing angle.

The results obtained with this set-up are summarised in **Figure 7**.

The top speeds are now a bit closer to their real-world counterparts, in particular at Le Mans, while the lap time deteriorates by about 0.7 seconds. This could suggest that either Toyota had a relatively high downforce and drag set-up, or the team simply had relatively high drag, compromising the car's top speed, though that seems unlikely.

Interestingly, with the high downforce configuration considered in the second run, the Porsche Curves sector time does not improve. This is partially due to the higher drag but also to the aerodynamic balance shift toward the rear, which negatively compensates the higher downforce and should in fact help in those corners.

This could hint at Toyota deliberately running a higher downforce set-up, while at the same time having the 'right' aerodynamic balance, even if top speed suffers as a consequence.

This study focused only on the general downforce and drag level and the aerodynamic balance, nothing else was changed. Other parameters, such as

The simulations presented here need to be used directionally, to isolate trends, without focusing too much on the lap times

ride heights, could still have a sensible influence on both lap times and top speed.

A comparison between the minimum (in black) and the maximum downforce run (in red) is shown in **Figure 8**.

One final detail emerging from Toyota's onboard videos is how the Japanese team seemed to have opted for a very long seventh gear. This was shown by a big rpm drop when shifting up from sixth.

As a side note, the regulations only allow two gear ratios set for the whole season, and the longer seventh gear was employed at least at Monza and Le Mans. At Spa Francorchamps, the Toyota drivers stayed in sixth on the longest straights, at least in qualifying, which hints at the alternative gear ratio choice.

Running the model with an arbitrarily longer seventh gear, and forcing the simulation to stay in sixth gear on the longest straights only at Spa, produced the results shown in **Figure 9**.

Top speeds further reduce and at Le Mans they are now very close to the average logged on track. Here, this 'detail' seems to be worth about 0.1 seconds.

AWD vs RWD

One very sensible topic to discuss, both for the LMH class itself, but also with respect to the plans to balance LMH and IMSA LMDh vehicles, is the effect of having a front electric motor, making cars so equipped all-wheel drive when speed exceeds 120km/h.

Assuming everything else to remain the same, what is the performance benefit of choosing this option? And how does it affect tyre degradation?

				Lap Time [s]			Gap [s]			
Circuit	Results	BoP	Ambient cond	Actual	Theor	Avg Top Speed [kph]	Act [s]	Act [%]	Theor [s]	Theor [%]
Spa	2021 Qualy	520kW	8.9° C, 963 mbar,	120.747	120.747	307.8	Ref	Ref	Ref	Ref
	Sim - LDF Trim	1040kg	48.1% Hum	120.472		313.9	0.275	0.228	0.275	0.228
Monza	2021 Qualy	515kW	31° C, 989.7 mbar,	95.899	95.899	313.3	Ref	Ref	Ref	
	Sim - LDF Trim	1066kg	48% Hum	95.33		320.9	0.569	0.593	0.569	0.593
Le Mans	2021 Qualy	515kW	18.2° C, 1008.4 mbar,	203.9	203.549	323.9	Ref	Ref	Ref	Ref
	Sim - LDF Trim	1066kg	74% Hum	201.918		328.9	1.982	0.972	1.631	0.801

Fig 6: Pole position performance at Spa, Monza and Le Mans vs simulation results in minimum downforce trim

				Lap Time [s]			Gap [s]			
Circuit	Results	BoP	Ambient cond	Actual	Theor	Avg Top Speed [kph]	Act [s]	Act [%]	Theor [s]	Theor [%]
Spa	2021 Qualy	520kW	8.9° C, 963 mbar,	120.747	120.747	307.8	Ref	Ref	Ref	Ref
	Sim - HDF Trim	1040kg	48.1% Hum	120.612		310.5	0.135	0.1118	0.135	0.112
Monza	2021 Qualy	515kW	31° C, 989.7 mbar,	95.899	95.899	313.3	Ref	Ref	Ref	Ref
	Sim - HDF Trim	1066kg	48% Hum	95.436		317.8	0.463	0.483	0.463	0.483
Le Mans	2021 Qualy	515kW	18.2° C, 1008.4 mbar,	203.9	203.549	323.9	Ref	Ref	Ref	Ref
	Sim - HDF Trim	1066kg	74% Hum	202.659		324.5	1.241	0.609	0.89	0.437

Fig 7: Pole position performance at Spa, Monza and Le Mans vs simulation results in maximum downforce trim

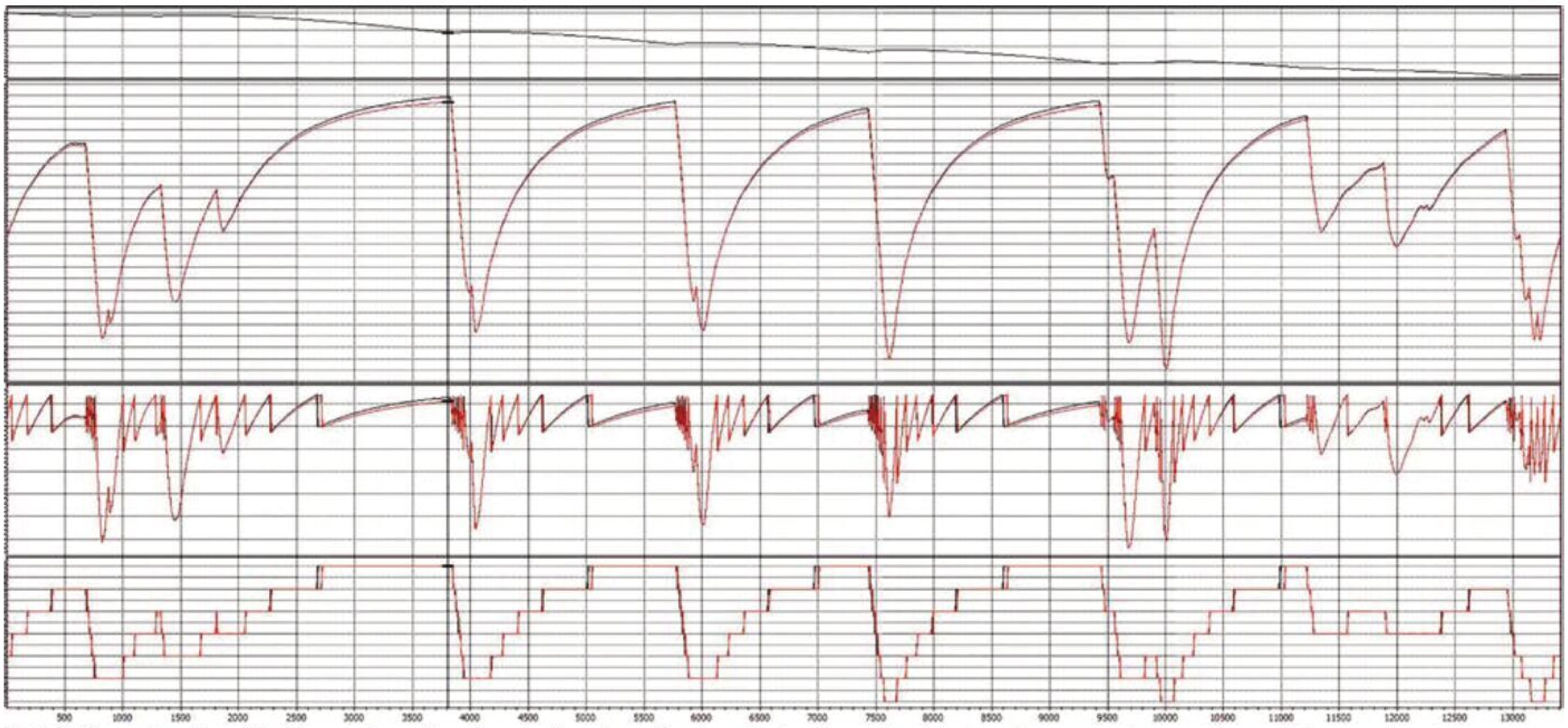


Fig 8: Minimum downforce (black) vs maximum downforce (red) configuration. From the top down, the plots show the compare time, speed, rpm and engaged gear

				Lap Time [s]			Gap [s]			
Circuit	Results	BoP	Ambient cond	Actual	Theor	Avg Top Speed [kph]	Act [s]	Act [%]	Theor [s]	Theor [%]
Spa	2021 Qualy	520kW	8.9° C, 963 mbar,	120.747	120.747	307.8	Ref	Ref	Ref	Ref
	Sim HDF Long 7th	1040kg	48.1% Hum	120.607		310.2	0.14	0.11594	0.14	0.116
Monza	2021 Qualy	515kW	31° C, 989.7 mbar,	95.899	95.899	313.3	Ref	Ref	Ref	Ref
	Sim HDF Long 7th	1066kg	48% Hum	95.444		316.8	0.455	0.474	0.455	0.474
Le Mans	2021 Qualy	515kW	18.2° C, 1008.4 mbar,	203.9	203.549	323.9	Ref	Ref	Ref	Ref
	Sim HDF Long 7th	1066kg	74% Hum	202.759		323.3	1.141	0.560	0.79	0.388

Fig 9: Pole position performance at Spa, Monza and Spa vs simulation results in maximum downforce trim and with longer seventh gear ratio

						Tyres Friction Energies	
		Lap Time [s]	Top Speed [kph]	Delta [s]	Delta [%]	Front Tyres Delta [%]	Rear Tyres Delta [%]
Low Downforce	AWD	201.918	328.9	Ref	Ref	Ref	Ref
	RWD	202.488	328.9	0.57	0.281	-2.631	11.609
High Downforce	AWD	202.659	324.5	Ref	Ref	Ref	Ref
	RWD	203.193	324.5	0.534	0.263	-2.448	12.724

Fig 10: Results of low downforce and high downforce runs with AWD (above 120km/h) and RWD transmission

To answer these questions, the models with low and high downforce set-ups were re-run, removing the assumption of having an all-wheel-drive transmission, complying to LMH rules. It is important to underline how the approximations considered here in modelling the electric motor driving the front wheels (assuming constant torque distribution between front and rear axles) likely lead to an underestimation of the positive effects of this architecture.

The results are shown in **Figure 10**.

The first factor that can be extracted from **Figure 10** is how the lap time improvement (between 0.5 and 0.6 seconds) depends on the aerodynamic configuration. The higher the downforce, and the portion of it acting on the rear wheels, the smaller the gain produced with an all-wheel drive application.

Besides pure performance, also critical is how the tyres are stressed with and without the front motor helping to accelerate the car out of the corners. This can be estimated by calculating the tyre friction energies over a lap. The higher the value of this metric, the harder the tyres are working and, likely, the quicker their degradation. As shown in **Figure 10**, a rear-wheel-drive car would produce friction energies 2.4-2.6 per cent lower at the front than an all-wheel-drive vehicle, but 11.6-12.7 per cent higher at the rear. In other words, while a rear-wheel-drive car would save some work on the front tyres, the additional stress on the rear tyres would be much higher than with an all-wheel-drive solution.

Figure 11 can help in providing a feeling about the differences between RWD and AWD cars.

The compare time and speed trace clearly show most of the gap is produced when the car accelerates out of slower corners.

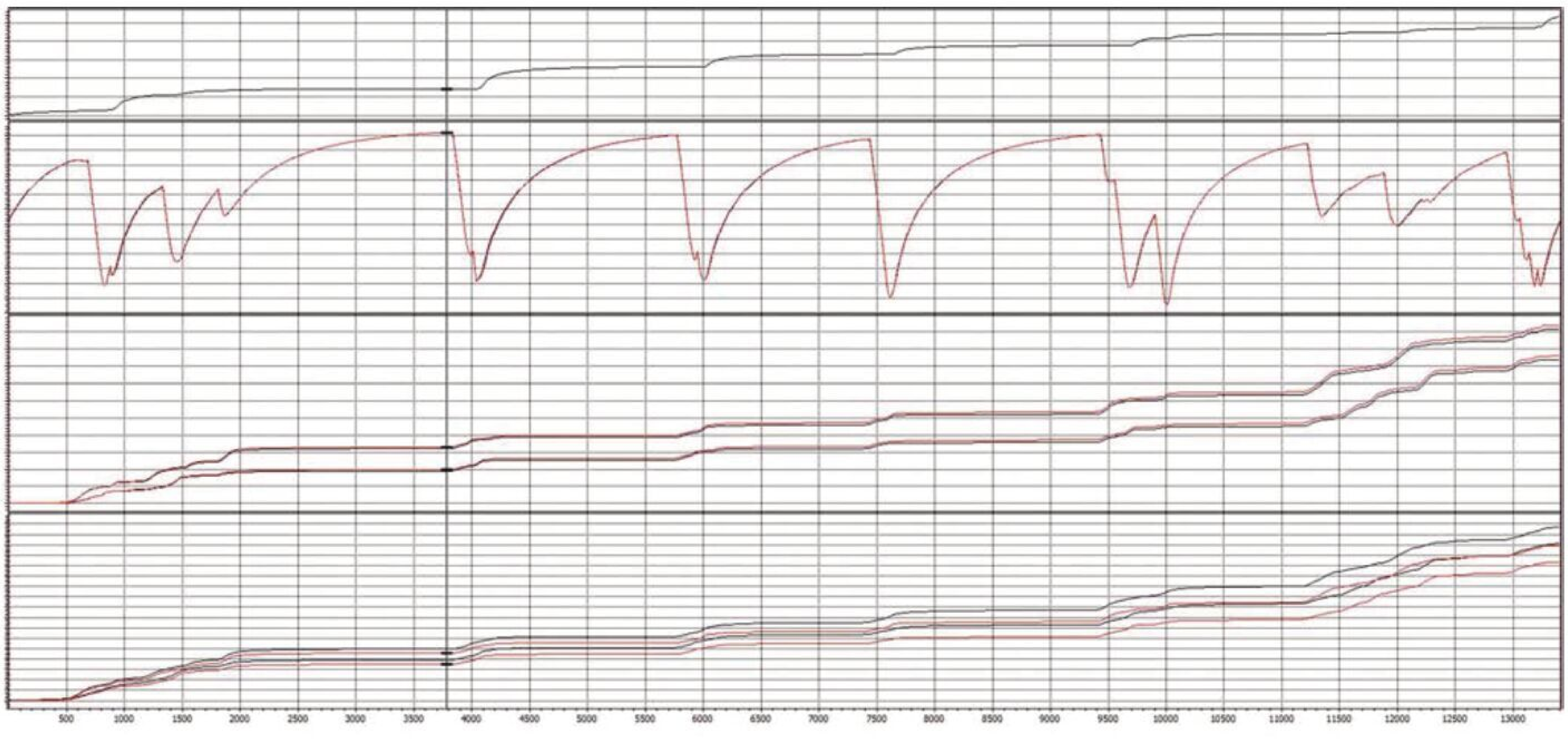


Fig 11: AWD (red) vs RWD (black) simulation runs. From the top trace down, comparisons are shown of time, speed, front tyre friction energies and rear tyre friction energies

In those sections, the compare time jumps upward, while the red speed trace lies clearly above the black one.

The tyre friction energy traces give a visual feeling about the difference between the two architectures. At the end of the lap, the difference between all-wheel drive and rear-wheel drive for the front tyre energies is much smaller in magnitude than the same difference for the rear tyres, as anticipated by **Figure 10**.

		Lap Time [s]	Top Speed [kph]	Delta [s]	Delta [%]
Low Downforce	AWD	201.918	328.9	Ref	Ref
	RWD - non-Hyb	201.549	330.5	-0.369	-0.183
High Downforce	AWD	202.659	324.5	Ref	Ref
	RWD - non-Hyb	202.355	326.04	-0.304	-0.150

Fig 12: Results of low downforce and high downforce runs with AWD (above 120km/h) and RWD transmission, with the RWD model set up according to 2021 Glickenhaus BoP. All other parameters remained unchanged

Compensation scheme

To compensate for the gap between AWD and RWD architectures, the regulations give some breaks to non-hybrid, rear-wheel-drive cars. The rulebook clearly stipulates RWD vehicles can use wider rear tyres (34/71-18) and slightly narrower fronts (29/71-18), while Glickenhaus was allowed to run at the maximum allowed peak power (520kW) and minimum weight (1030kg) for the whole of the first WEC season.

So, what is the expected performance of non-hybrid cars, assuming the above breaks are fully exploited?

To assess this point, the model described here, in both low and high downforce configuration was run at Le Mans, leaving everything unchanged but with the following parameters:

- Mass of 1125kg (1030kg for the car, as for Glickenhaus BoP, 75kg for the driver and 20kg of fuel)
- Maximum power at the wheels of 520kW (no tolerance nor deviation from nominal power curve)
- 29/71-18 front tyres and 34/71-18 rears

Because of the absence of data about the non-hybrid tyres, the author used a statistical approach to scale the hybrid car's tyres' grip to match the new dimensions.

Other parameters, like tyre vertical stiffness, camber effects and expansion at speed have been left unchanged.

The results of the runs performed with the RWD model are shown in **Figure 12**, where the 'Toyota-like' car is still taken as a reference.

While this analysis is based on important approximations, and despite the lack of proper data and the number of assumed parameters, such as aero maps, weight distribution and suspension geometry all being the same for cars with such different architecture, the results still seem to show the regulators did a decent job in trying to balance the different vehicles. The non-hybrid concept produced better lap times by about 0.3 seconds in both low and high downforce configurations. At Le Mans, the gap seems to be mainly down to power and top speed, with the non-hybrid models outperforming the hybrid by about 2.5km/h in both runs.

This can be clearly appreciated in **Figure 13**, where the results of the low downforce runs with the hybrid (in black) and non-hybrid (in red) are compared. The non-hybrid model clearly has an edge, thanks to a higher power and top speed, but accelerating out of slow corners it is still at a disadvantage compared to the hybrid, despite its lower mass and the higher power. The black speed trace always lies above the red one at the exit of low-speed corners.

The results seem to show the regulators did a decent job in trying to balance the different vehicles

In cornering situations, the rear-wheel-drive vehicle is slower, probably because of a worse, mid-corner understeer tendency. This could be cured by changing car balance (both aerodynamically and mechanically), but that would stress the rear tyres more and likely hurt performance over a stint, with the car tending more toward oversteer with worn rubber.

How different the two configurations would perform on longer stints is a topic for another article, though the more even tyre degradation of an all-wheel-driven car would surely give it an advantage in this respect.

One final critical point to stress is that the analysis presented here was based on the assumption that, with the exception of tyre characteristics, engine power, vehicle mass and, of course, the absence of an electric motor powering the front wheels, all the other key parameters remain the same for both hybrid and non-hybrid models.

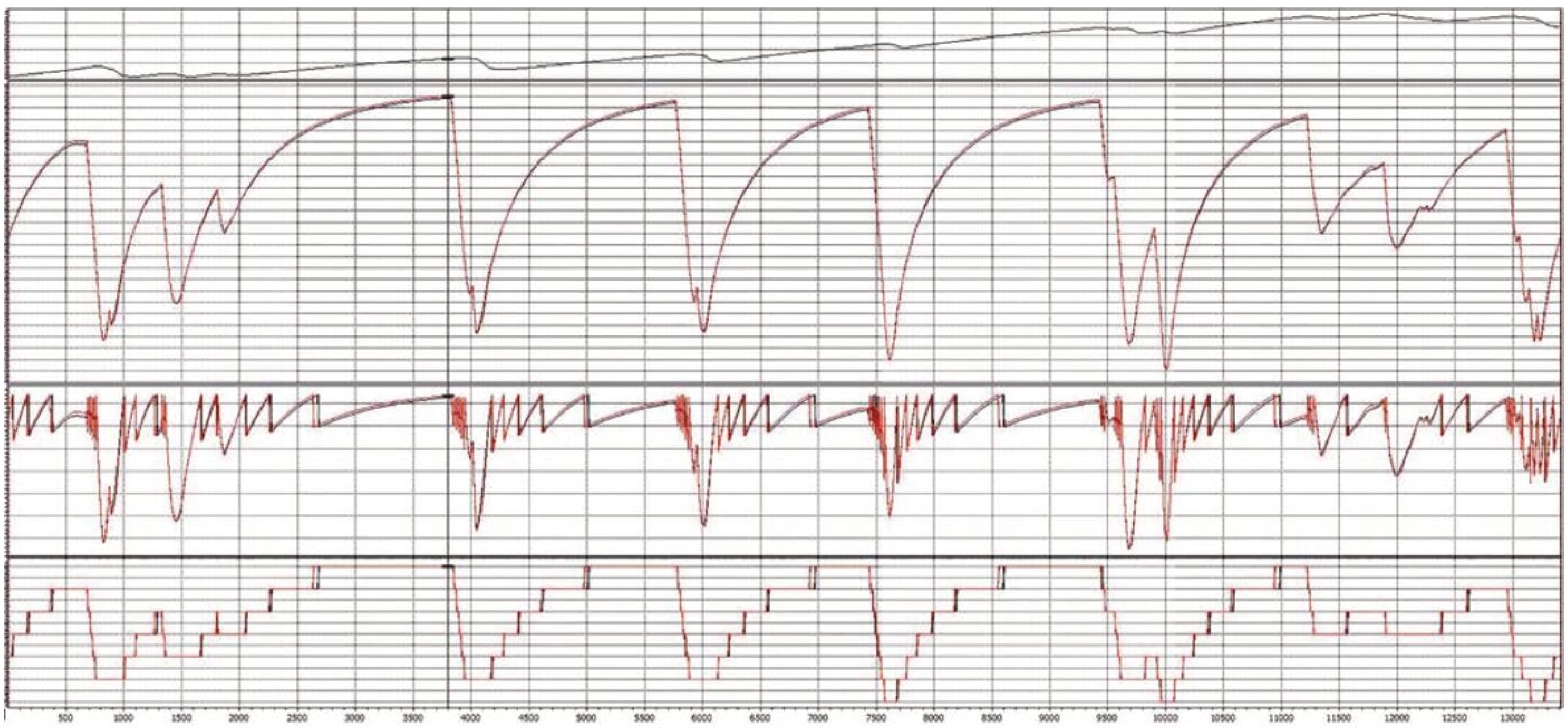


Fig 13: AWD, hybrid model (black) vs RWD, non-hybrid model (red) simulation runs. From the top down, traces are compare time, speed, rpm and engaged gear

All images: John Travis

Part of the design brief was that the car have a 'family resemblance' to the 2004 Ferrari F1 car. Rory Byrne designed that one, and was tasked with overseeing the A1GP project in a similar capacity. Shown is the finished car at Fiorano for its first test

Full speed ahead

Former technical director and chief designer, John Travis, explains how A1GP's second generation racecar was conceived, designed and delivered as a full grid in under a year

By JAMES KMIECIAK

Known as the 'World Cup of Motorsport', A1GP began in 2005 / '6 with a racecar based on a Lola B05/52 chassis, powered by a 3.4-litre Zytek V8, and clad in a stylised bodywork and aerodynamics package that led to it being dubbed, not altogether unkindly, 'the Batmobile'.

It produced ferocious racing and partisan crowds wherever it travelled, which, in turn, attracted future F1, WEC and DTM drivers and engineers to the international one-make series. By the 2007 / '8 season, it regularly delivered what F1 was lacking at the time – overtaking and spectacle.

After three seasons of events, in which nations rather than teams and drivers competed against each other, and with what later transpired to be somewhat curious finances bubbling beneath the surface, a decision was made to build a brand new car. The reason for this sudden shift was led by an offer from a new engine supplier. Coming off the back of the dominant Schumacher era in F1, and with a recently crowned champion in Raikkonen, nobody hid the fact this was largely a marketing exercise. The *caché* of Ferrari involvement brought undoubted value to the series and helped to promote Ferrari's road car division. However, even that brand value wasn't enough as the category lasted for just one further season (2008 / '9) before it went into liquidation.

While there were definite cost constraints, a big effort was made to build a good car, with a progressive aero envelope

The reasons for the collapse are outside our remit here, but the story of the genesis of the second generation A1GP car is fascinating. It is not simply another archetypal tale of how motorsport engineered a top-quality product in a very short timeframe. It's the story of how an idea became a grid full of cars to F1 quality of the day in a matter of months, starting from scratch with no factory and no personnel.

Former technical director and chief designer on the project, John Travis, shares his recollections of events with *Racecar*.

First contact

Travis, previously chief designer at Lola and at Penske Cars, had been working as technical director (special projects) at Epsilon Euskadi since 2004, and it was while testing at Estoril in 2007 that Bruce Homes, the chief operating officer of A1GP, came to see him. 'Bruce invited me to design the new car but, to be honest, I wasn't keen at first. However, he explained the link with Ferrari was serious, and suggested I went to meet the people at Ferrari to see just how serious they were.'

And so, in October 2007, Travis travelled to Maranello and met with Jean Jacques His, Mario Almondo, Rory Byrne, Mauro Rioli and Marco Galli, names enough to be convincing of the manufacturer's serious intent.

'However, they then wanted to come and see our factory.' It was a reasonable request, except no facility existed at that point.

'How do you sustain a building when contracts come along as and when?' asks Travis. 'But, by the time they visited in mid-November, we had put together a factory for them to visit.'

Travis went to URT Composites in Bognor Regis, southern England, a company he'd already had dealings with, and director, Max Cox, pointed out that the unit adjacent to URT was available, with office space and was ideal for the purpose.

'It was just an empty shell,' remembers Travis with what might be a guilty grin, 'so we had to make it look like a functioning factory. Our PC suppliers loaned us some PCs, we got some office furniture and sat some CAD guys in front of them.

'Mario Almondo, then Ferrari F1 technical director, and Rory Byrne came over, so we took them to see our UK-based 'preferred suppliers', which included Xtrac, and only after that showed them the 'A1GP Technology factory'. We explained it was all new, and where everything would be.

'The deal came together very quickly from there and we then had to set up in earnest. The decorators and builders were in over Christmas and we opened on 2 January 2008.'

The overall approach to the design and manufacture of the new car was to create a strong team of preferred suppliers that, in addition to Xtrac, included Pankl, ATL and Penske Dampers, who were all persuaded to join the project. URT ultimately did all the composite work too, as we shall see later.

'We utilised our key partners' expertise and people to do R&D, as well as manufacture components,' explains Travis, 'while we just had six or seven design people.'

Byrne, who had extended his tenure as F1 designer at Ferrari in a consultative capacity, had been asked to oversee the A1GP 'Powered by Ferrari' project in a similar capacity. As Travis notes, that played a big part in its success: 'Rory and I got on, and this was a strong link in our ability to do this.'

Design brief

As ever, the design specification was based on key aspects and broad principles, the most important of which being, as Travis recalls, 'the Ferrari brand be protected at all costs, so what they wanted, they got.' From there, he went on to write a detailed specification with every single item spelled out.

'The car was only going to run on category two circuits (Portimao, Zandvoort, Brands Hatch, etc) and this determined lap times, power requirements and performance parameters. Importantly, the car had to have a 'family resemblance' to the [Byrne-designed] 2004 Ferrari F1 car. Ferrari helped us a lot with that.'

'But F1 cars are very expensive, and we were a one-make formula with cost constraints, so there were target costs for production, including amortisation of design, moulds and so forth.

'But we weren't going to follow the notion of creating a car for the sake of it. We made a conscious decision to make it very good, with a progressive aerodynamic envelope. You have to remember that the teams were only going to see their cars when they arrived at the circuits. There was no opportunity for them to test and develop in between races.

How an idea became a grid full of cars to F1 quality of the day in a matter of months, starting from scratch with no factory and no personnel

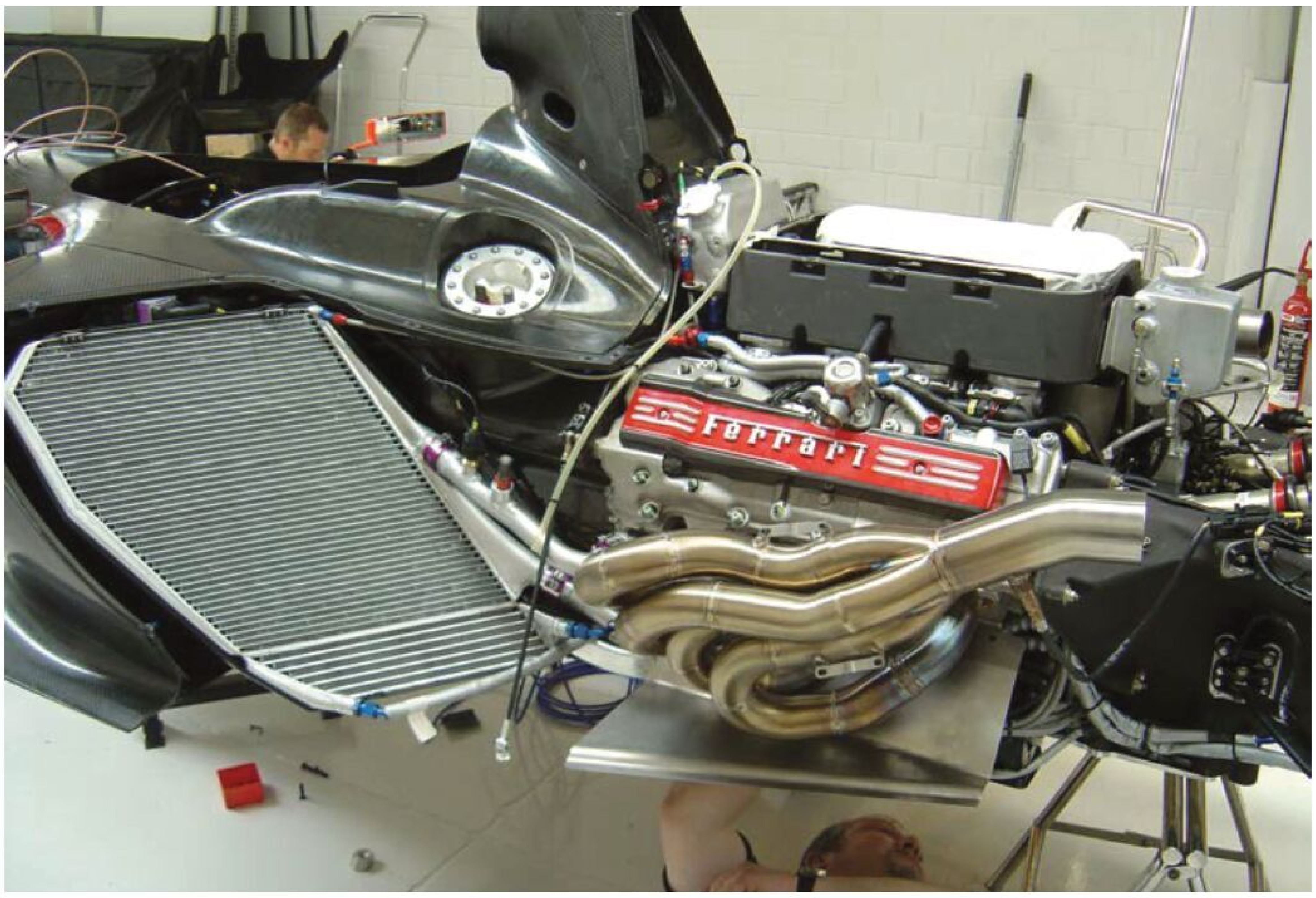
'Other key areas were a rear diffuser and ground effects, wide track, but not a wide front wing because we knew how to make front wings benign when a car steered. But a really important aspect was weight distribution, due to the heavy engine.'

Because Ferrari only made genuine race engines for its F1 programme, the new A1GP racecar was to be powered by a road car V8 from the manufacturer's new F430 model. However, at 160kg, it was some 40kg heavier than the previous generation's Zytek V8.

'Whatever we did,' continues Travis, 'we couldn't get the weight distribution far enough forwards, so we were going to overload the rear tyres. We were offered the tyre sizes from the World Series by Renault car, which had about 450bhp, but we were targeting over 600bhp. That meant we were not going to be able to balance the car.'

So Travis and colleagues paid a visit to French tyre manufacturer, Michelin, in Clermont Ferrand. 'We showed them our simulation results, which demonstrated that we would have an oversteering car, and asked them for a bigger rear tyre. With the might of Ferrari beside us, they agreed and made a new bespoke mould for us. This then tied in with buying new rims from OZ.'

Travis is in no doubt that without the Ferrari involvement this special dispensation from Michelin would not have been made on the tyres, and it was a crucial factor in helping to make the car work well.



The engine was a 600bhp, roadgoing V8 from Ferrari's F430 model. Its 160kg weight caused some problems with balance

'[due to the road car engine] we couldn't get the weight distribution far enough forwards, so we were going to overload the rear tyres'

The design office team. This was pretty much the size of the operation

Lean and mean

'Recruiting and getting infrastructure in were big issues at the start. My ex-Penske Cars colleague, Paul Baker, and I spent Christmas 2007 – working around the builders and decorators – wiring in PCs ahead of the contract designers coming in on 2 January. Thankfully, we got a good group of people in, who got stuck in and worked closely and well together.

'Remember, we had no car design history, no archive of parts and no schedule. Peter Morgan, who was with me at Epsilon Euskadi, did the scheduling with a huge Gantt chart on his wall. Alan 'Hatchett' Harris was the buyer. We had to put him in a soundproofed room as he took no nonsense from any suppliers. Martin Dixon was production manager. Stuart Allen was in charge of composites with Paul Baker, and Mario Saccone worked in Bognor and Italy on finite element analysis. We were a very mean, lean team.

'We also had a very good inspection department, and a very good inspector / storeman, who set up a system so all stores were bar coded and everything was made in batches to keep unit costs down. The bar coding meant we knew exactly what parts we had, and each car comprised over 2500 parts. To think that one man did all that is incredible. We practically built the inspection room around the inspector during the early stages.'

Returning to the point made earlier about utilising the skills and resources of their preferred suppliers, Pankl designed, analysed, manufactured and tested all of the suspension, including the uprights (made using electrical discharge machining, EDM) and wishbones.

Xtrac did the same with the gearbox. Travis' team designed its cast magnesium casing, Xtrac then doing the finite element analysis before manufacturing it.

'It was an unusual gearbox because of the high crankshaft height,' remembers Travis. 'Ferrari didn't want to do a specialist sump for the engine, which meant we had to have a big shear plate under the engine. This meant the crank was high, 125mm above the bottom of the shear plate, so the gearbox ran input drop gears to step the gear cluster down to lower the c of g of the transmission. The drop gears also stepped down the torque, which allowed slimmer, lighter change gears, too.'

It was a longitudinal, six-speed transmission (based on Xtrac's successful F1 arrangement in use since 1995) and the ratios were changed from the front end.

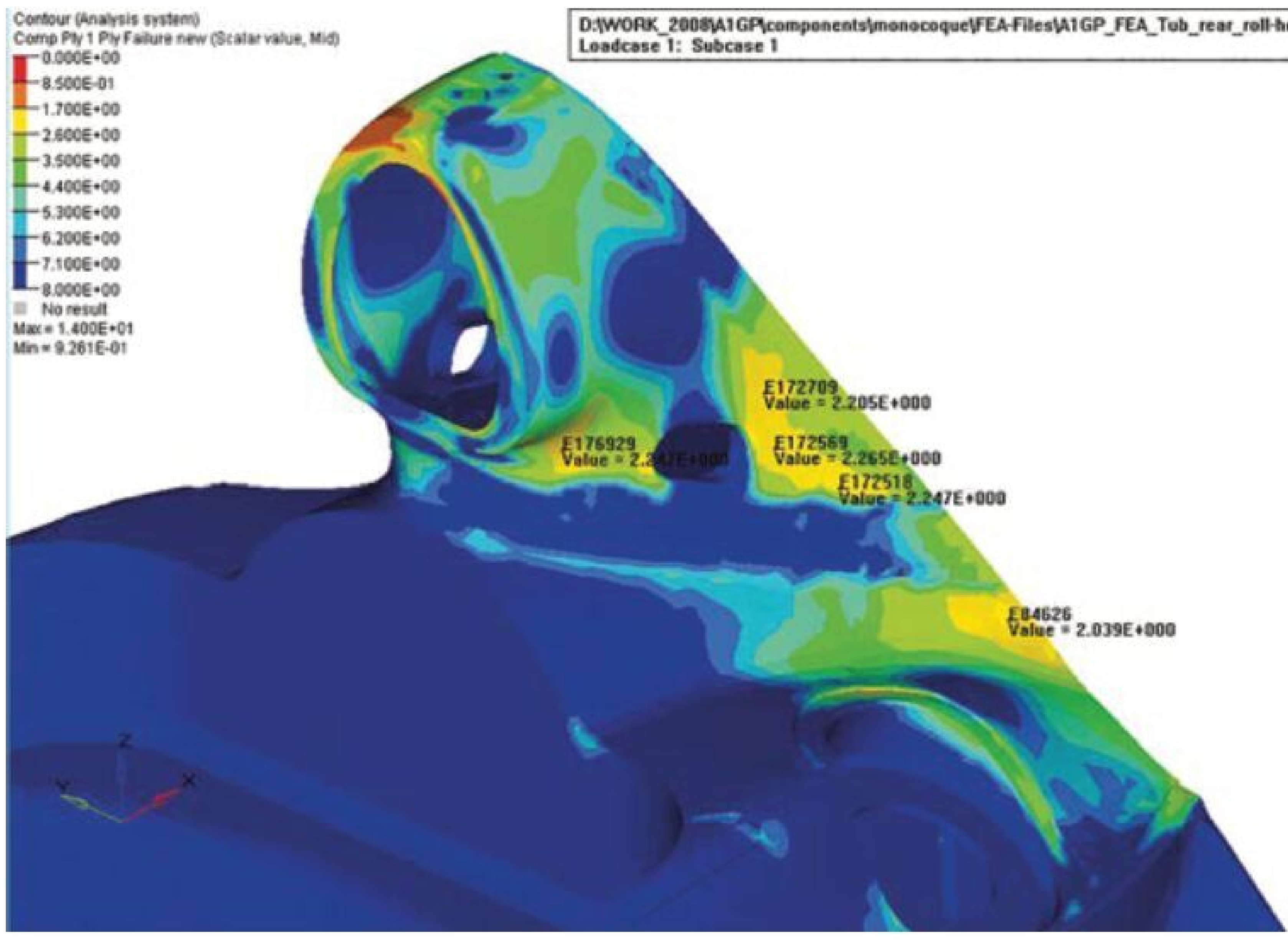
'The sump only had scavenge ports on the right-hand side, meaning we'd lose oil pressure in long right-hand corners as the oil was not returned to the oil tank and was retained in the engine. So we had to re-design the oil tank baffling to reduce this issue. As we hadn't got a car at that point, we were testing an oil tank lying on its side in the workshop so we could simulate the *g* forces!'

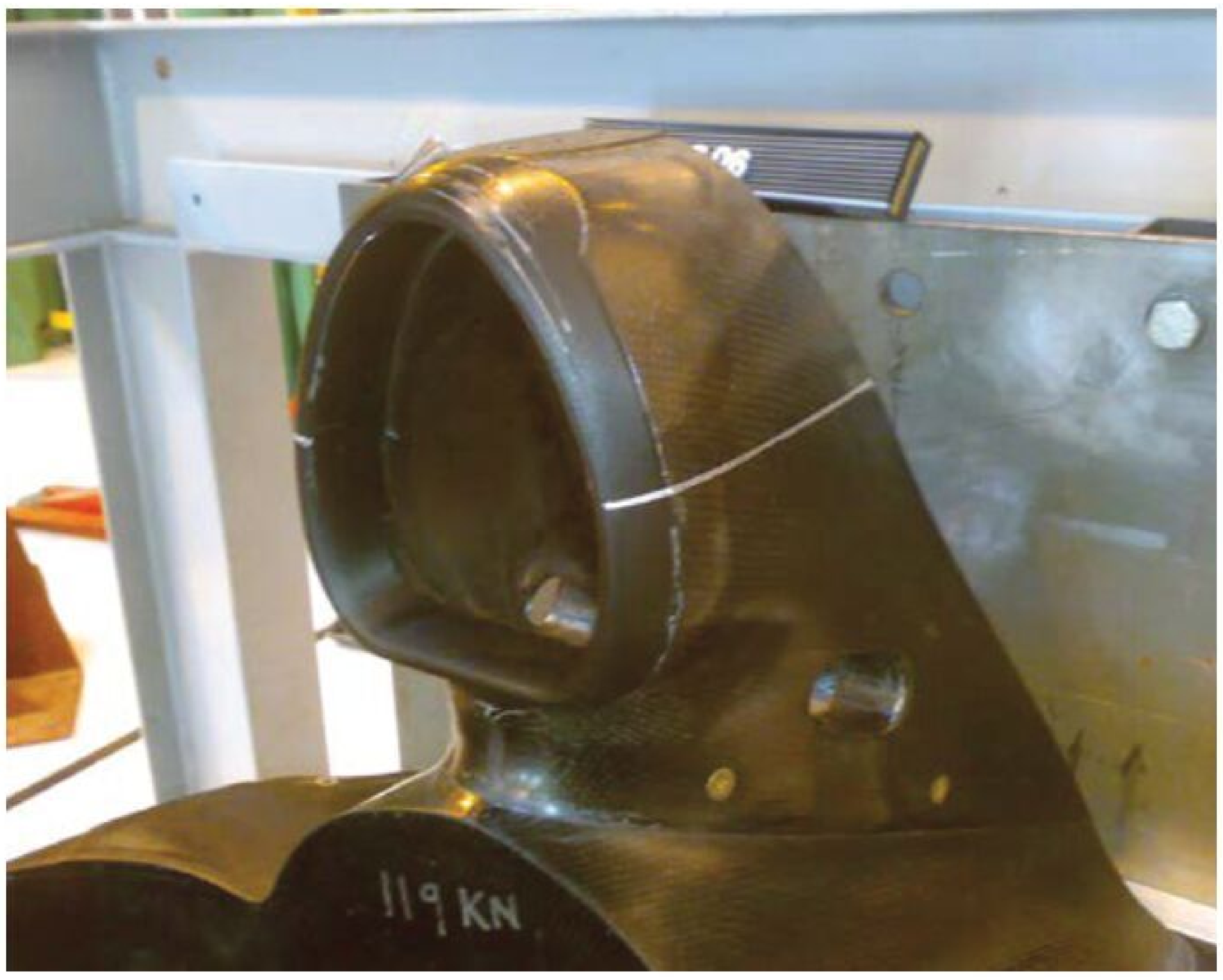
When a chassis was complete, and the engine installed, track testing of the baffled oil tank was undertaken at Snetterton as the team found the long linking right handers of The Bomb Hole and Coram perfect test beds for similar tracks on the proposed calendar.

In keeping with F1, carbon brakes were employed for stopping duties. 'Brembo made bespoke calipers and discs for us,' continues Travis. 'We wanted long life material so, through Michael Messina, they provided endurance specification material.'

Unsurprisingly, given the Ferrari connection, Magnetti Marelli was the preferred partner for the electronics, and Anton Stipinovich the man who designed the systems for the A1GP car.

'The electronics were bloody complicated, and included the Bosch direct injection fuel





FEA was used to develop the car's FIA-standard, Formula 1-spec composite roll hoop, which was made from a billet aluminium mandrel clad with a carbon fibre exterior

system, gearbox control, anti-stall and so forth. Every car had live telemetry on it, and Ferrari had screens of data on every car, each of which had GPS. Ferrari did not want to see an engine blow up in public, so there were two technicians per car. It was an entourage.'

Keeping cool

'All of that was led by Michelotto, who tuned the engine. They put us under extreme pressure to get everything right, especially with regard to cooling. We were in Maranello every two weeks for technical reviews. I remember they gave us heat rejection figures from the dyno, and there was a total of 190kW from the oil and water systems, and I was just thinking, 'how are we going to cool this?

'The friction in a production engine is a lot higher than a normal race engine. So the oil cooler was a heat exchanger in the v of the engine, and from wind tunnel work and pressure coefficients from the radiators we calculated we needed 3470cm^2 of cooler area. Once we had that knowledge, Docking Engineering made bespoke coolers for the car.

'Ferrari also had a specific warm-up procedure we had to follow, involving starting, warm up, seal the system, pressurise it with a small hand pump, and off you go. Even the coolant we used was controlled [by Ferrari].'

Having discussed the chassis requirements with many well-known composite manufacturers, it was decided to bring everything as close to 'in-house' as possible, by using the next-door neighbour, and experienced motorsport chassis manufacturer, URT Composites.

'All our composites parts were made by them. We had a close relationship in all respects and it just made sense to use them and be in control, and perhaps achieve some cost savings, too. But it was all very high-quality stuff, including a composite roll hoop to pass the FIA's standard F1 tests. It was unheard of to make a composite roll hoop for a one-make series, but we developed a process using a Rohacell 'spider' with a carbon exterior and an aluminium billet internal mandrel, for which we had calculated the thermal expansion to consolidate the moulding. That enabled us to develop a production process.

'Even the [40 per cent scale] wind tunnel model was bloody good, despite being for a one-make series. All the aero development was done with this in the ex-Penske tunnel at Southampton University, there was no CFD.

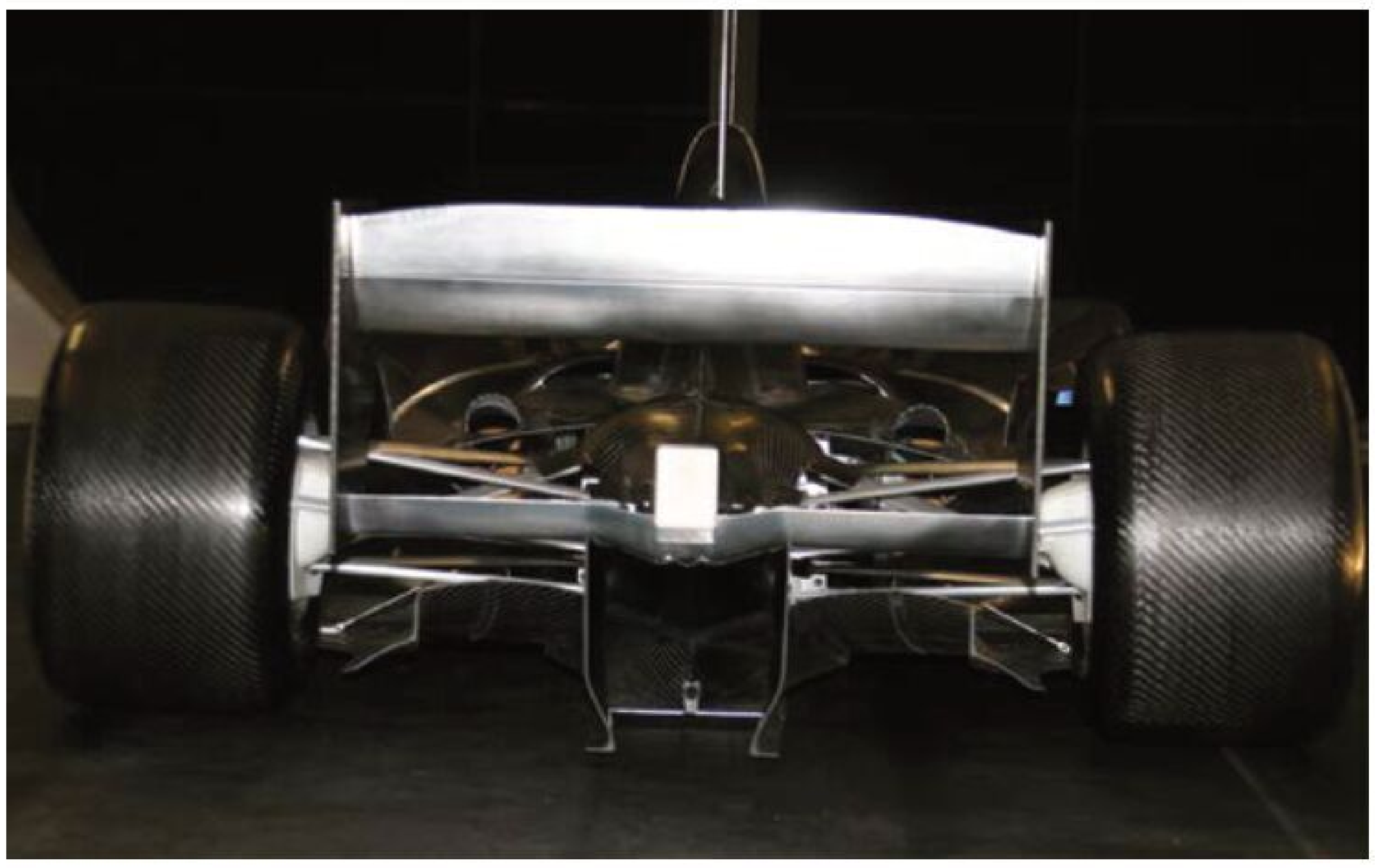
Ferrari did not want to see an engine blow up in public, so there were two technicians per car. It was an entourage

Production process

'But because of the overall timescale we had, there was absolutely no development time, which meant we had to do a lot more FE analysis to help get things right first time.

'Despite that, we did have a catastrophic side impact test failure at TRL [Transport Research Laboratory, Wokingham, UK] and we had already committed to production on the basis of a good prototype… Fortunately, it wasn't actually down to the side impact structure itself, it was because the restraints had allowed the tub to move and tip so the load was off axis and the impact structures were not applied head on. They consequently folded and collapsed.

'So we cut that chassis in half and glued the good half for a re-test. And then we re-tested another chassis in a machined buck that prevented any movement and it was okay. We also then sleeved the side impact tubes in top hats bonded to the chassis.



All aero work was done with a 40 per cent scale model in the tunnel at Southampton University

No CFD was used for the car's aerodynamic development, only the wind tunnel work

'We also made a fundamental error on the ergonomics and had to make a 50mm longer chassis and impact test it, which meant making one extra chassis for one team [and two spares].'

Pre-production testing

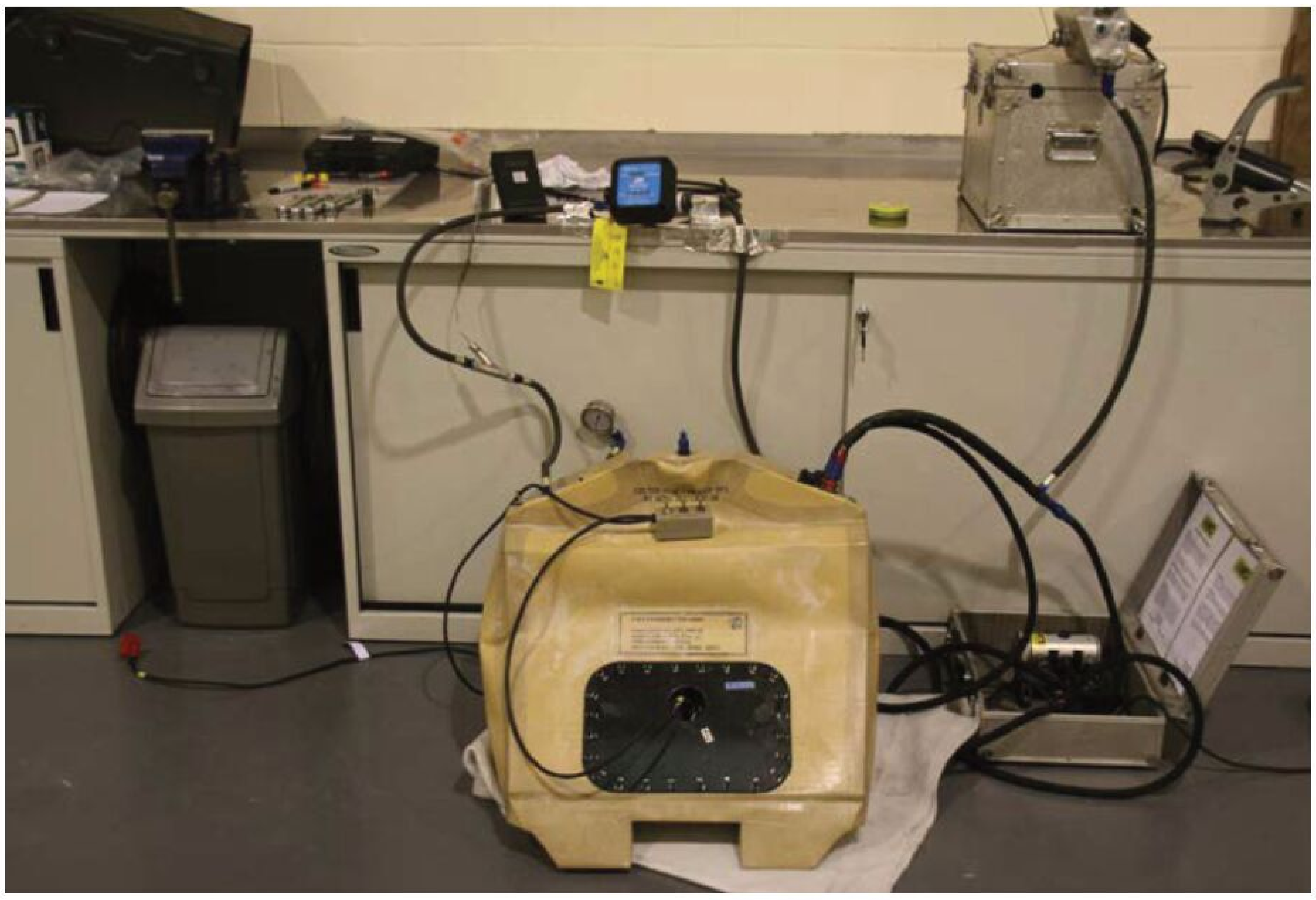
By May 2008, the first car was completed and shipped to Ferrari's own test track at Fiorano where it began a relentless testing schedule across Europe via Imola, Jerez, Mugello, Paul Ricard and Magny Cours, before it was joined three months later by the first production car at a cold and wet Silverstone in autumn.

With just two months to go before the season started, the test car had completed over 5000km with very few issues. Those that did raise their head were reported back to the design team, a solution identified, prototype parts made and shipped out before being signed off for application to the 'production' cars, after having proved themselves at the next test session.

But even with such an intense pre-production testing schedule, problems were still being identified during the season, as parallel testing was undertaken. One such issue related to the fuel system after the cars tested at Kyalami in South Africa, as Travis recalls: 'Due to the heat and altitude, the fuel was boiling in the tank and vaporised by the time it reached the injectors. This caused huge misfires. We had to develop a suitable low-pressure scavenge pump set up and pressurised accumulator system, which meant heating a full fuel tank to 60degC in the middle of the factory floor to simulate the problem before developing a solution, manufacturing a grid full of kits and shipping them out to be fitted weeks before the race.'

Which leads us on to the question, how did a relatively small group of engineers build 25 cars in such a short period of time, while at the same time ensuring the individual teams had long enough to learn how they went together prior to the first race?

The test car was subjected to a brutal three-month testing schedule at tracks across Europe, including Imola (shown)



With no time for track testing, the team had to get creative in the factory. Here the fuel tank is being pressure tested

Slot cars

Travis explains: 'The teams were all invited to book their build slot and send over their own team of mechanics. We would then have three to four cars being built at the same time under the supervision of our three primary mechanics.'

This also led to Travis asking himself how he would best like to approach the race engineering of a one-make series.

'So we built a full vehicle dynamics programme for the teams to do their own simulations. We got it ready for the first race, with Karl Niklas giving lectures to all the teams on how to use it. We gave the teams everything, so they didn't need to develop their own programmes.'

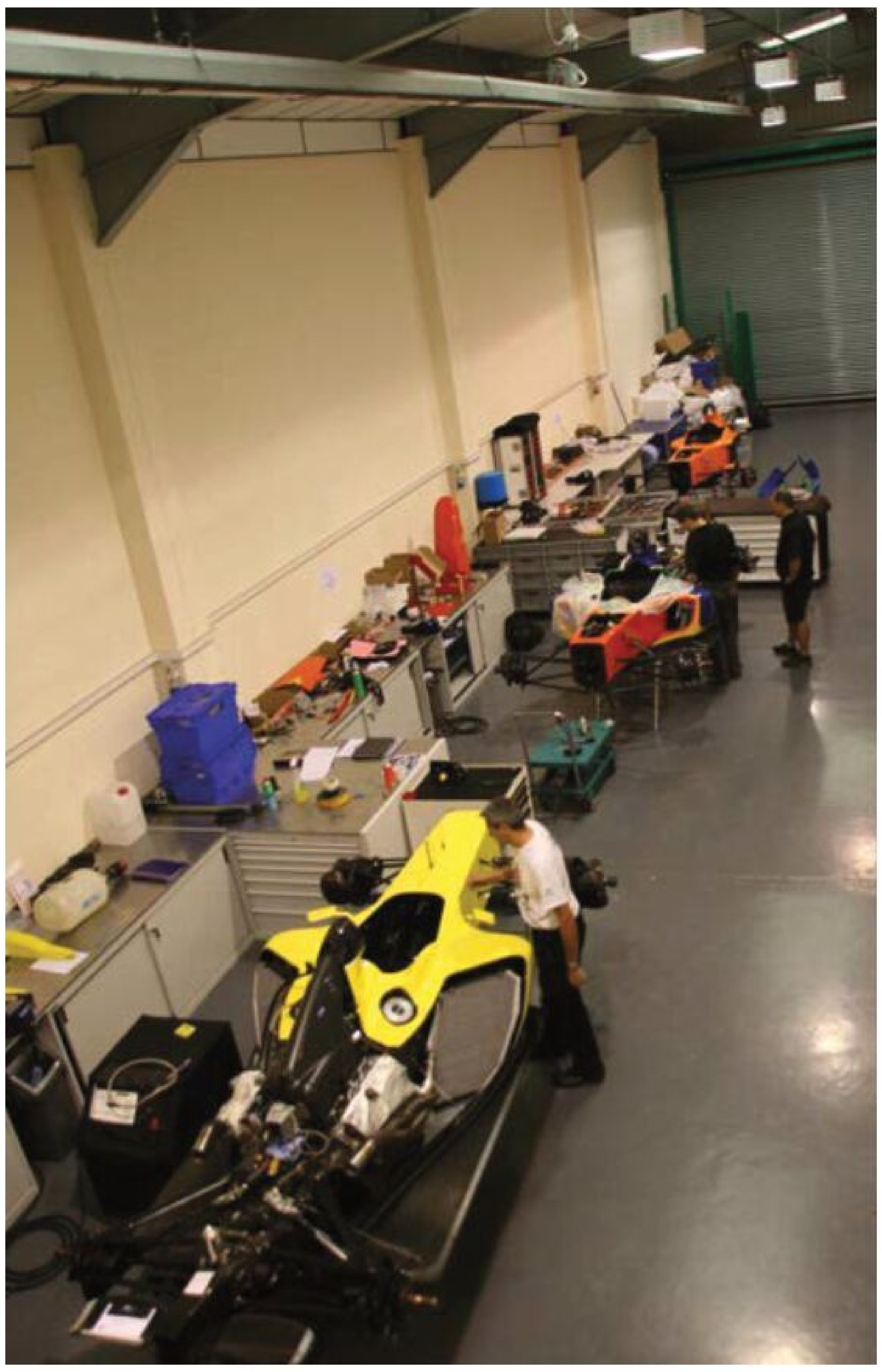
As for transport between races. 'There were two 747s with the whole grid in. They were full of 'shack packs', moved by Delivered on Time [DoT], the freight company. Ultimately, they were the biggest creditors, and the cars were sold to a South African buyer [AFRIX Motorsport] in 2015 to settle that debt.'

With mention of the series' demise put aside, the collaboration, ingenuity and organisation shown by Travis and his team ensured the 17 teams that contested the first race at Zandvoort on 5 October 2008 were able to get up to speed quickly, compete on a level footing and set lap times over three seconds faster than had been achieved in the previous generation of A1GP car. And do all of that in front of packed grandstands.

'The timeframe for a hi-tech car, despite being one-make, was a credit to everyone involved. I don't know how we managed it all, but everything just seemed to drop into place,' Travis says while reflecting on the enormity of the project, before concluding, 'It was an honour. We were the only people to build a Ferrari-badged car outside Maranello. It was definitely one of the best projects to have worked on.'

The 17 teams… were able to get up to speed quickly, compete on a level footing and set lap times over three seconds faster than had been achieved in the previous generation of A1GP car

Racecar's *thanks to John Travis for his time and valuable insights to this project.*



Cars were built three at a time, and teams invited to book a slot and send over their own mechanics to be involved

What happened next?

For John Travis, it was a sideways step as he now puts all the lessons learned from his years in motorsport into his new passion, electric motorboats.

With the majority of current EV technology focussed on the automotive sector, he noticed nobody was designing and manufacturing systems to help reduce $C0_2$ emissions of leisure boats.

'A lot of people were just dropping automotive systems into boats that were not designed for this type of duty cycle. Our system uses a cascade motor system, rotary engine range extender and an optimised energy management system to ensure maximum range and efficiency.'

The Furyan F35 also utilises a monohull built from flax fibre, as being trialled in motorsport to reduce manufacturing emissions by 75 per cent over GFRP and 90 per cent over CFRP. With input from CFD expert, TotalSim, the hull has been designed to improve efficiency at the range of speeds associated with this style of cruiser.

Taking the racing links a step further, the motor control system is linked to the onboard Navionics (sat nav) to ensure when a route is plotted the motors can be optimised to guarantee the target journey range is achievable, much like planning pit stop strategy in an endurance race.

For more information, visit www.furyanmarinetechnology.com

Furyan's innovative flax fibre hull has been developed in CFD to optimise efficiency in the speed range it is designed for

Clearly, range is a big issue with electric boats, and so Furyan's motor control unit is linked to its Navionics system to ensure a journey is achievable

The anti-antis

When it comes to longitudinal dynamics, many engineers consider front anti-dive and anti-lift, or rear anti-squat and anti-lift, as separate entities. Here's why that is the wrong approach

BY CLAUDE ROUELLE

Several years ago I remember experimenting with some vehicle dynamics software alongside one of my colleagues, and we were wondering how much higher we could keep the front edge of the splitter in the braking zone by increasing the anti-dive from 20 to 30 per cent, while all other car characteristics were kept the same. That included tyres, aero map, masses, their c of g position, their inertia, suspension kinematics, stiffness and damping, brake balance, brake inputs and subsequent deceleration.

The answer looked strange at first as, on average, the car was 2mm lower. 'But we just increased the anti-dive so, if anything, the front splitter should be higher,' we thought. Until my colleague noticed the rear had gone up 10mm more!

Reason being we had more pitch angle, and that is why the front splitter was lower, despite an increase in front anti-dive.

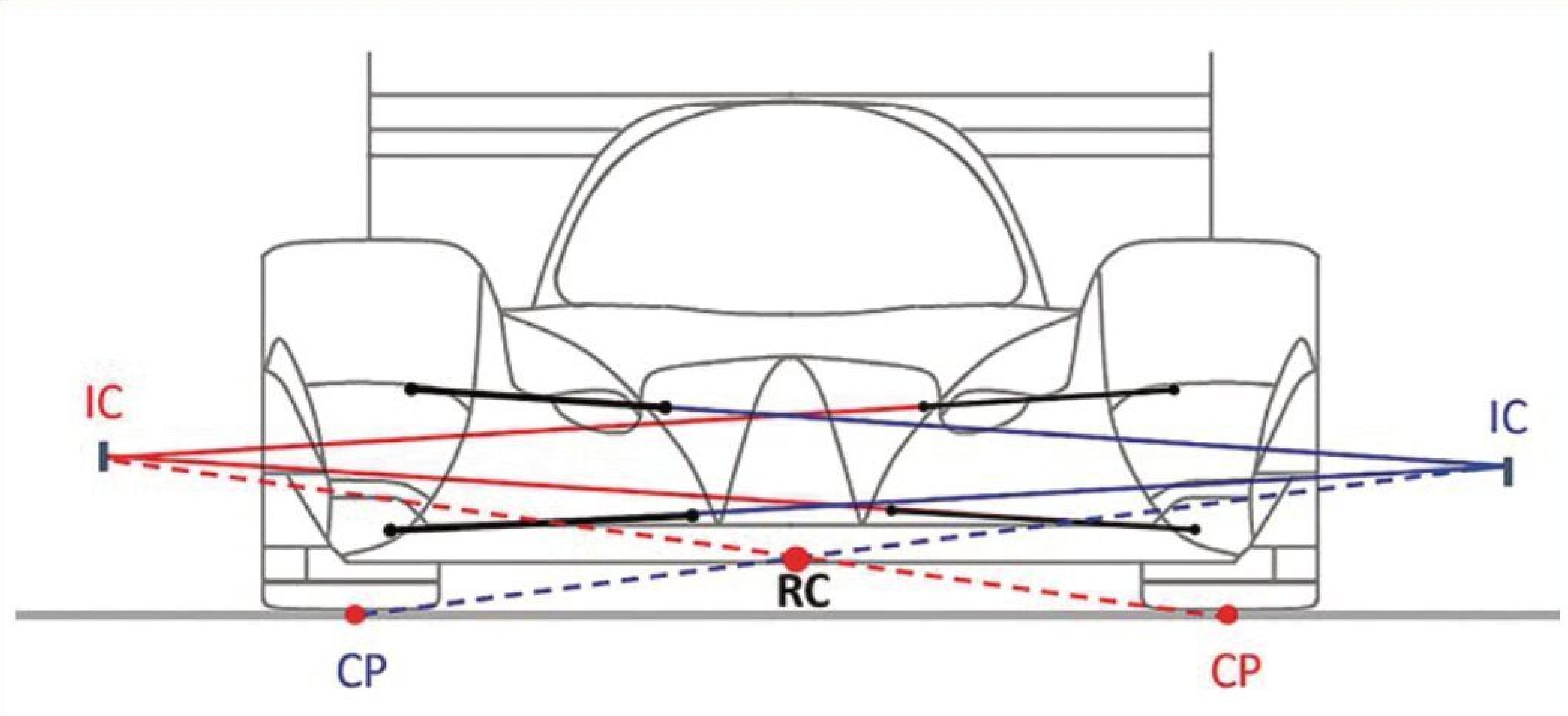
A few questions were subsequently raised: where is the point (or axis) about which the suspended mass rotates in braking or acceleration, and how did those point coordinates change when we altered the anti-dive? We were speaking about the pitch centre (in 2D) or pitch axis (in 3D).

2D load transfer

When we study a simple 2D lateral load transfer (only the front, or only the rear suspension) we link the left and right kinematics to define the roll centre. That roll centre position then helps us to split the suspended mass load transfer in a geometric load transfer (passing from one tyre to the other through the top and bottom suspension linkages) and elastic load transfer (passing from one tyre to the other through springs, dampers, maybe bump stops, and an anti-roll bar).

But why in a simple 2D longitudinal load transfer would we look at only the front suspension anti-dive properties, ignoring the rear, or look at the rear suspension anti-lift, ignoring the front?

Fig 1: Simplified definition of the kinematic roll centre



If we go this way, why don't we discuss independently in lateral dynamics the kinematic 'anti-up' of the outside wheel and the kinematics 'anti-down' of the inside wheel?

I believe the reason for this is that most engineers are not familiar with the notions of pitch centre and pitch axis.

So, let's start the presentation of this topic with a quick review of the kinematics roll and pitch centre definitions.

Figure 1 shows the simplified definition of the kinematic roll centre in 2D. Each wheel is assimilated to an infinitely small thickness disc that has only one point of contact with the ground: the contact patch, or perhaps we should say the contact point (CP). The intersection of the extension of the suspension wishbones gives the instantaneous centre (IC) of rotation of the wheel about the frame.

The intersection of the lines joining each IC to its relative CP gives us the kinematic roll centre (RC). That is the instantaneous centre of rotation of the suspended mass about the ground.

All that because of the theorem of Aronhold-Kennedy (that we will not develop here) that says the three instant centres must be aligned.

It is a very simplified definition for several reasons. Firstly, this a 2D view. The front and rear pick-up point of the top wishbone and / or the bottom wishbone do not necessarily have the same z coordinates. Ditto for the bottom wishbone.

Some engineers consider that by switching to 3D, instead of intersecting two lines they just need to intersect the top and the bottom wishbones planes to find the wheel instant axis of rotation about the chassis. That approach would be proved wrong because, if there is bump steer, the wheel movement will define an envelope of which the instant axis will not be the intersection of the top and bottom wishbone planes.

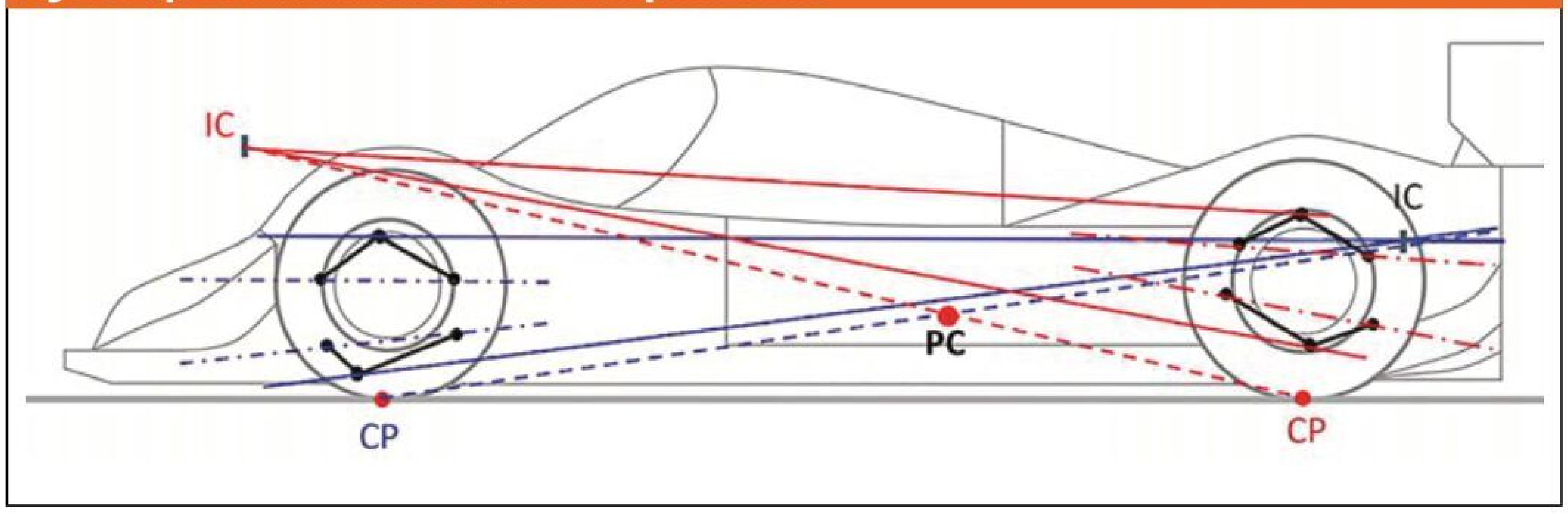
To finally question the validity of this top and bottom wishbone planes intersection method, let us ask ourselves a simple question: where are the top and bottom wishbone planes in a five-link suspension?

Other limitations include the fact there is no such thing as a tyre contact patch. In the real world, there is a contact surface and the centre of the forces acting in that surface is not necessarily in its geometric centre.

Once the car is in roll, the roll centre won't stay in the same place. That is why we refer to it as an instantaneous roll centre. If in static the roll centre depends on the

Why in a simple 2D longitudinal load transfer would we look at only the front suspension anti-dive properties, ignoring the rear?

Fig 2: Simplified definition of kinematics pitch centre



intersection of the extension of the top and bottom wishbone lines, dynamically the roll centre trajectory will be determined not only by the intersection of the extension of the top and bottom wishbone lines, but also by their relative length.

Lastly, there is no compliance. The tyre is considered rigid and the suspension upright, linkages and chassis are considered undeformable.

All that said, we will use **Figure 1** as it is: a simplified representation of the kinematic roll centre.

2D pitch centre

Figure 2 shows the simplified definition of the pitch centre in 2D, in blue for the front suspension, and in red for the rear suspension. For the top and bottom wishbones we draw them parallel to the axis connecting the inboard (chassis) pick-up points that pass through the corresponding outboard (upright) pick-up point.

The intersection of these lines defines the side view instantaneous centre of rotation of the front and rear wheel about the chassis. Just as for the kinematic roll centre, the intersection of lines from each IC to its wheel CP give us the kinematic pitch centre.

A few comments on this.

1. In **Figure 1**, we can see that if the left and right suspensions are symmetrical, the kinematic roll centre will be in the middle of the car. If the suspended mass c of g is also in the middle of the car the roll centre will be right under this c of g. At least at rest.

   However, in **Figure 2**, we can see the front suspension is not necessarily a 'mirror' of the rear one. In fact, that is rarely the case. Therefore, the pitch centre is not necessarily in the middle of the wheelbase and / or right under the suspended mass c of g.
2. As we have seen in previous articles that analyse lateral load transfer, jacking force is a function of the initial position, as well as vertical and lateral movement of the kinematic roll centre. We will not debate here the usefulness of a kinematic roll centre above or under the ground. There are good and bad arguments for both.

   What we need to understand is that the closer the roll centre is to the ground (above or under it), the smaller the angles between the ground and the lines from the wheel CP and its IC, which could make the roll centre lateral movement quite difficult to control.

   If, however, with a very small change in roll angle variation, and only one of the two IC to CP lines inclined vs the ground changes, the roll centre will necessarily move sideways a lot. And neither the car, tyre nor driver likes a roll centre that crosses the inside or outside wheel plane.

   The same consideration is valid for the effect that low angles between the ground and the lines side view IC to wheel CP could do for the pitch centre longitudinal movement.
3. Some books, with which I disagree, use the intersection of the top and bottom wishbones' inboard pick-up points to define anti-dive and / or pitch centre. Why would we use points belonging to the suspended mass to describe the instantaneous centre of rotation *of the wheel*?
4. The reader can use their imagination here. If the lines that connect the front top and bottom wishbones' inboard pick-up points are as shown in **Figure 2**, but the lines that connect the rear top and bottom wishbones' inboard pick-up points are both parallel to the ground, the instantaneous centre of rotation of the rear wheel about the chassis will be

The vast majority of cars have four wheels, be they production or race versions, and the interactions between all four should be considered in any discussion of chassis dynamics

Jakob Ebrey

infinite and the line between that IC and the CP will be the ground itself. Which, in turn, will put the pitch centre at the front wheel contact point, with not a lot of front suspension movement expected.

There could be some serious issues in designing one suspension with 'anti' and the other one without.

5. Suppose a racecar designer draws a car with no anti-dive or anti-squat. The lines that connect the front top and bottom wishbones' inboard pick-up points are both parallel to themselves and to the ground (if the car itself is parallel to the ground). But, if the race engineer then decides to introduce some rake (a higher rear than front ride height) into the car set-up, the wishbones' inboard axes remain parallel to themselves, but not to the ground, and there will now be some anti-dive and anti-squat.

Fig 3: Basic definition of anti-dive

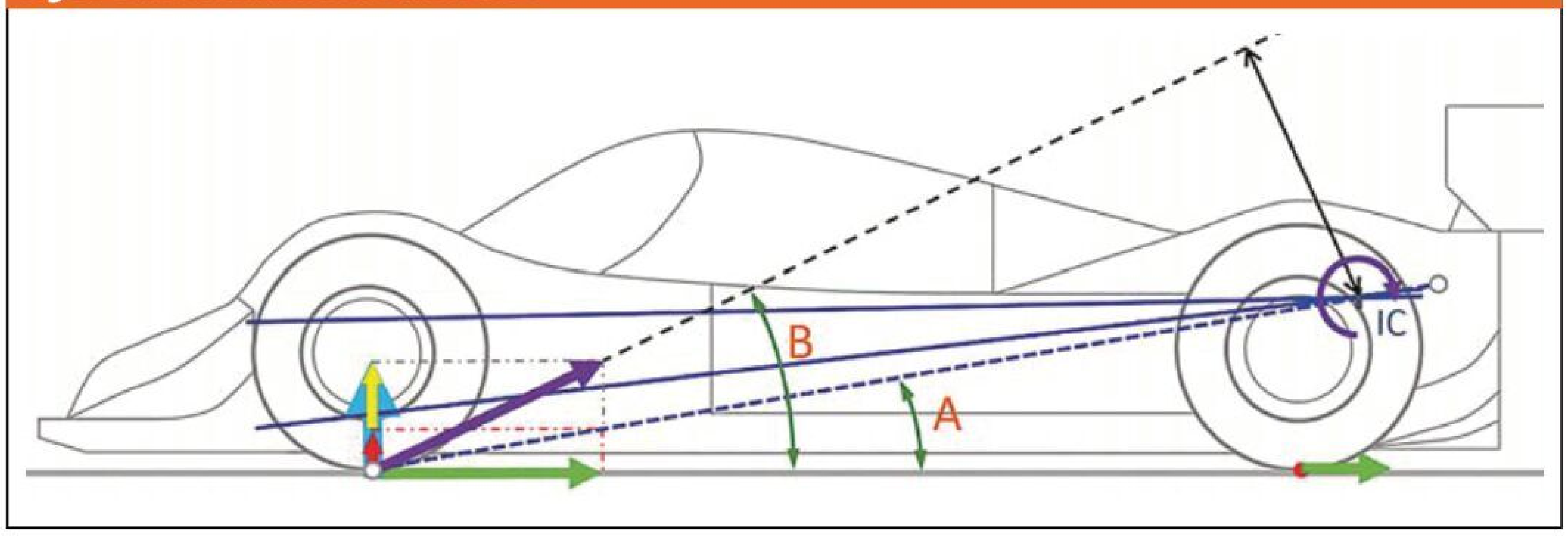
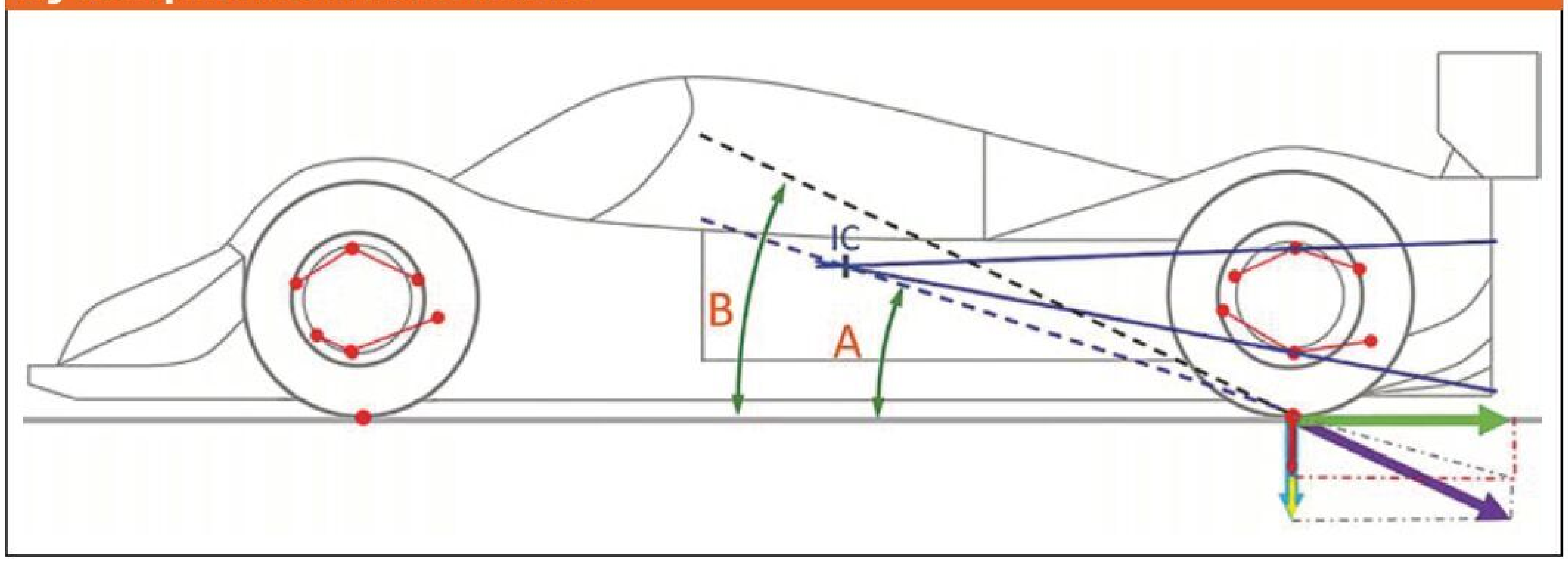


Fig 4: Simplified definition of anti-lift



Dive and squat

In **Figure 3**, we see the usual definition of anti-dive and anti-squat, with the green vectors showing the front and rear braking forces and the blue vector representing the suspended mass longitudinal load transfer, which is split into geometric (red vector) and elastic (yellow vector) load transfer.

What determines the distribution between the geometric load and the elastic longitudinal load transfers is the angle A, which is kinematics dependent as it is defined by the line that connects the front wheel CP with the side view front wheel IC.

The purple vector is the composition of the front braking force and the front suspended mass load transfer, while angle B by the inclination of that purple vector.

The anti-dive is defined by Atan (A) / Atan (B). Usually, we express this in percentage.

We now realise that anti-dive is a function of brake distribution. If the brakes were inboard, the purple vector would be originating at the wheel centre and angle A would be defined by the angle between the horizontal passing through the wheel centre and the line connecting that wheel centre and the IC.

On a hybrid car, such as recent LPM1, the anti-dive will have to be calculated twice: firstly, from the outboard brakes and secondly, from the inboard electrical motor.

Identical considerations are made for anti-lift in **Figure 4**.

Conclusion

What is the main point here? If we look at anti-dive, you focus on the front suspension, ignoring the rear. If we look at rear anti-lift, you focus on the rear suspension, ignoring the front. If, for the sake of absurd reasoning, we go this way, as shown in **Figure 5**, why not look at the 'anti-up' of the outside wheel, ignoring what happens on the inside wheel and where the roll centre is? Just as we would look at the anti-lift of the front wheel, ignoring what happens at the rear wheel and where the pitch centre is.

Why then would we speak about roll centre in lateral dynamics and not about pitch centre in longitudinal dynamics?

The whole suspended mass rotates about an instantaneous roll axis under lateral acceleration. The same suspended mass rotates about an instantaneous pitch axis under longitudinal acceleration. The car has four wheels. We can't look at the front suspension ignoring the rear, any more than we can look at the left suspension ignoring the right.

Slip Angle **is a summary of Claude Rouelle's OptimumG seminars.**

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

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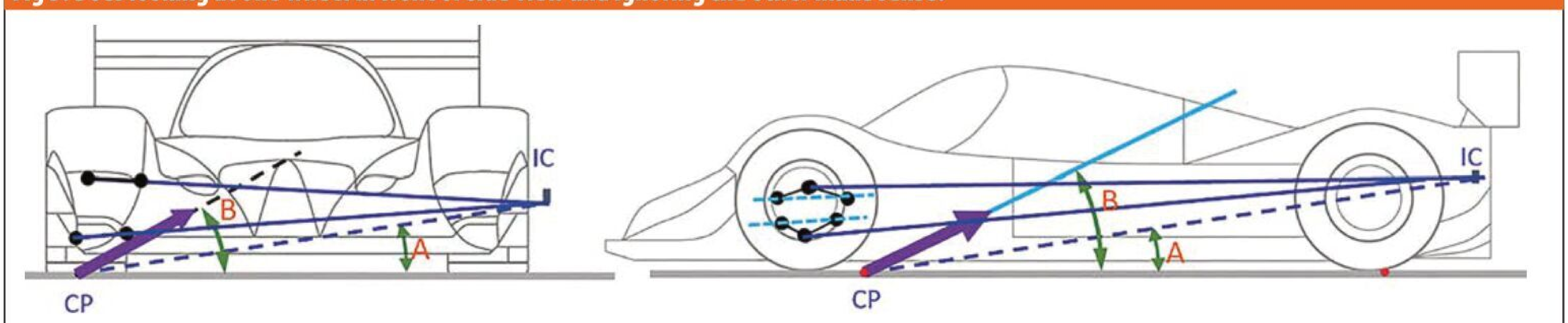
Fig 5: Does looking at one wheel in front or side view and ignoring the other make sense?



It is a common mistake in racecar engineering to focus on front and rear suspensions separately, yet their behaviours are directly interconnected, so a holistic approach is always better

Tubular belles

With spaceframe chassis, hybrid powertrain and more constrained aero, 2022 World Rally Cars are unlike any before. Racecar *investigates*

By LAWRENCE BUTCHER

For the first time ever in the history of rallying, cars competing in Rally1 share no major item whatsoever with the production cars they are based upon

'All of the cars are slightly different, where we've taken the regulations and adapted the architecture to how we want to best present our cars for overall performance'

Chris Williams, technical director at M-Sport

Dan Bathie

Rallying changed forever as the 2022 WRC season got underway in Monte Carlo. Since the genesis of the sport, competing cars have *always* been based on production bodyshells. Even in the radical days of Group B, the cars used limited run road car chassis. Though large chunks of the last generation WRC machines were chopped out to make room for rear differentials, and outer skins stripped away and replaced by carbon or Kevlar, they were still showroom models underneath.

The new era of Rally1 may look similar to last year, with pumped-up, steroid-fuelled version of the Yaris, Puma and I20, but none share a single major part with their common or garden roadgoing versions. Under the bodywork, now entirely composite in construction, sit tubular spaceframe chassis, encasing a spec hybrid system.

No longer are manufacturers constrained by rules tying them to particular models in their ranges, hence why Ford's Puma – a mini SUV – is sharing space on the stages with Toyota's Yaris shopping mobile, albeit a three-door, homologation special, thanks to the much-lauded GR version.

Staying alive

This then, is the future of rallying, and how we got here was best summed up by Hyundai's now departed (and much missed) former team principal, Andrea Adamo. Speaking when the final details of the rules were still being hammered out, and before Covid threw the world into disarray, Adamo stated in his endearingly blunt fashion: 'We need to be in a situation where a manufacturer can use the model that they need to sell. If we want to say alive, we need cars that will be acceptable to the marketing types.

'It's the manufacturers driving this sport, not the FIA or the promoters. Your board will tell you, this is the budget, I need to promote this model, end of discussion. There is no romanticism.

'The alternative is you don't have it. It's like my mother, you either eat your soup or you go to bed without dinner.'

So it was that rules dictating what are, in effect, silhouette racers came to be. And, in the opinion of one technical director, a framework established that will likely become the norm in rallying's future. As more manufacturers move towards EVs, road to rally car conversions will no longer be practical. Scratch-built chassis could become the only cost-effective way to create competition machines. Not to mention the safest.

When devising the new regulations, the FIA had two key considerations in mind: giving manufacturers flexibility to run a wider variety of body styles, while also incorporating safety features that were impractical if using a production car base.

For example, the space available for side impact protection, one of the biggest areas of concern in rallying, is now much greater. Packaging the hybrid system as far as possible from harm's way was also a prime consideration.

A new core

In overview, the central spaceframe incorporates three main hoops encapsulating driver and co-driver, with extensive triangulation between them. The lower door sections feature considerable reinforcement, with a passing resemblance to structures used in NASCAR's latest Stock Car chassis. The protection afforded by this reinforcement is augmented by large areas filled with energy absorbent foam of varying densities. Tied into this central 'cage are support structures for the front and rear suspension. Previously, the production chassis would extend to almost the furthest extremities of the cars. Now, the tube frames stop just after the front and rear axles centrelines, with only additions necessary to support the bodywork reaching beyond this point.

In the run up to, and during, the opening round of the season, the WRC's top-flight drivers certainly put the new safety measures to the test. During pre-season running Hyundai's Thierry Neuville had a spectacular off. The accident itself was not caught on camera, but the resulting carnage was, namely his demolished car sat down a ravine in a river.

Come the Monte, it would be M-Sport's young hot head, Adrien Fourmaux, who went for maximum air and style points, barrel rolling his Puma and coming to rest at the bottom of a cliff. In both cases, the damage looked more serious than it would have done on a 2021 car, due to most of the vestigial bodywork detaching, leaving the safety cell exposed. However, neither crew suffered more than bruised egos (and, in Fourmaux's case, a team starting to lose patience with his car-wrecking antics), testament to the phenomenal strength of the new machines.

Moveable freedom

The general opinion across the service park in Monte Carlo was that the clean-sheet chassis rules removed some problems, while creating new headaches. Toyota technical director, Tom Fowler, sums up: 'I think the total amount of freedom is probably about the same, it's more a shift in freedom.'

Fowler highlights the design of the front suspension crossmembers as an example. Here, the previous production-based rules required certain parts stay in their stock locations, and be worked around. 'Depending on your base car, this always gave a certain challenge and ruled out some concepts for sure. In that sense, the freedom is increased.'

Dan Bathie

Drivers are encased in a spaceframe chassis that are incredibly strong with essentially three hoops married by triangular struts

Lawrence Butcher

With safety a prime consideration, side impact structures have developed, with more space available for energy absorbing materials

Lawrence Butcher

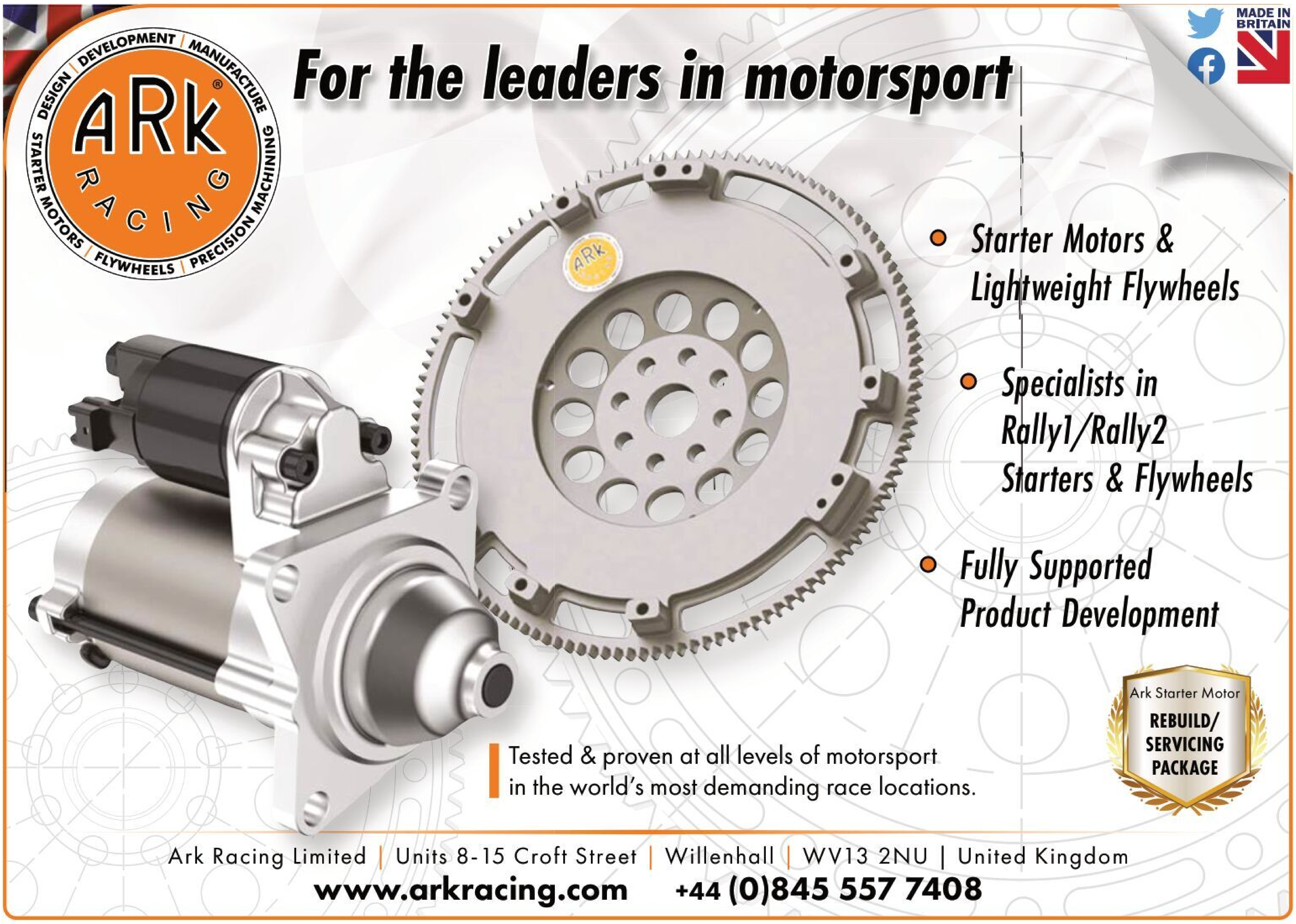
Lawrence Butcher

'I think the total amount of freedom is probably about the same, it's more a shift in freedom'

Tom Fowler, technical director at Toyota rally team

Lawrence Butcher

Different manufacturer treatments of suspension strut angle in relation to front axle centreline are already on display in the paddock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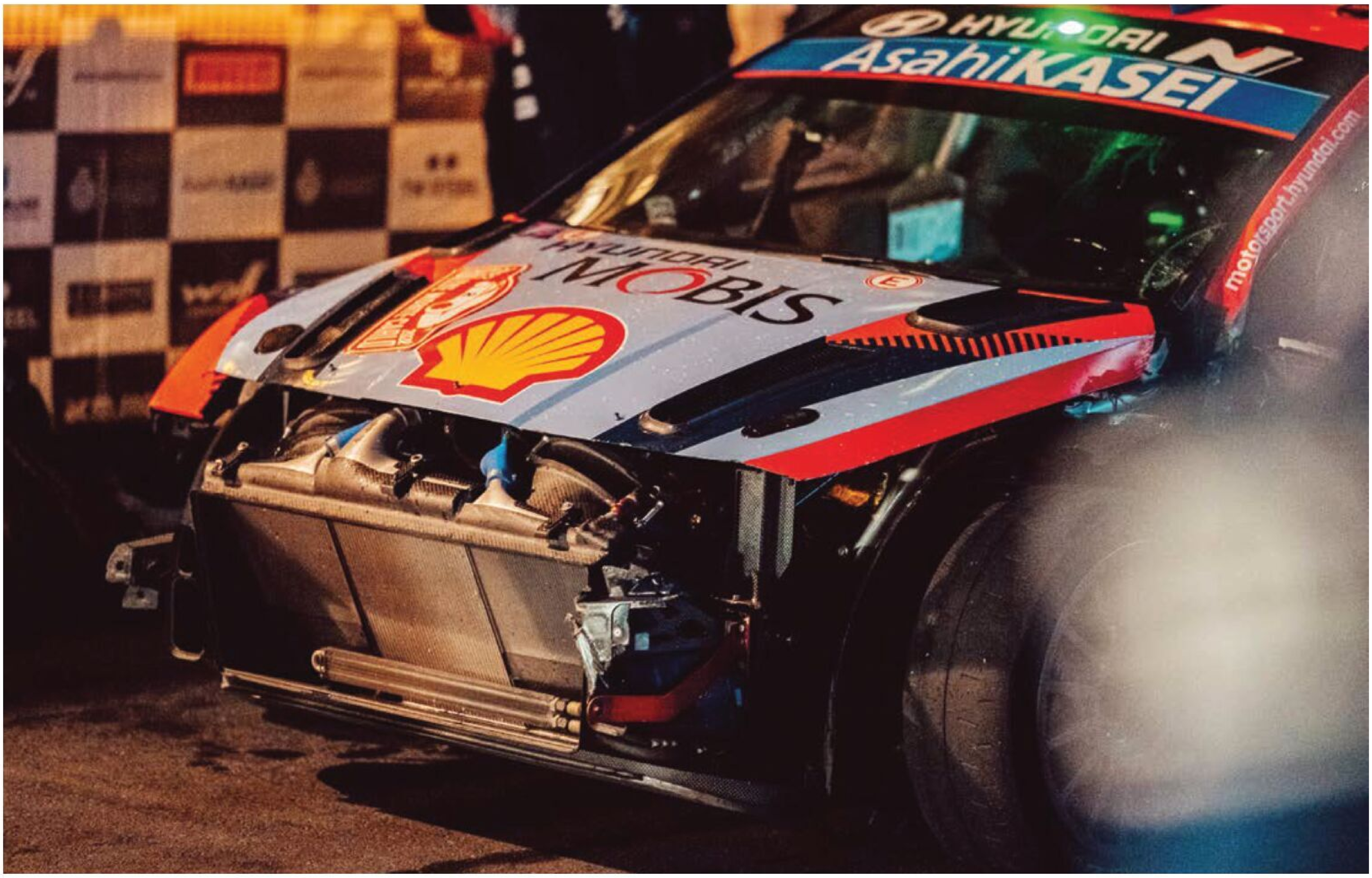


Dan Bathie

However, that's not the case everywhere, as his comments regarding the central chassis area show: 'The chassis and, more particularly, the safety cell is designed to an FIA regulation based on the crash testing calculations they performed. The result is that compared to the previous safety cell, there are more members involved, with an increase in the total number of tubular structures used, and the majority of those are fairly well tied down to their position. We have ended up with a fair few geometric constraints in the safety cell, and so the limitations have increased.'

M-Sport technical director, Chris Williams, agrees. 'We must all carry certain elements, and those elements must sit within certain volumes. We all have to work to a quite a tight measurement in certain areas.

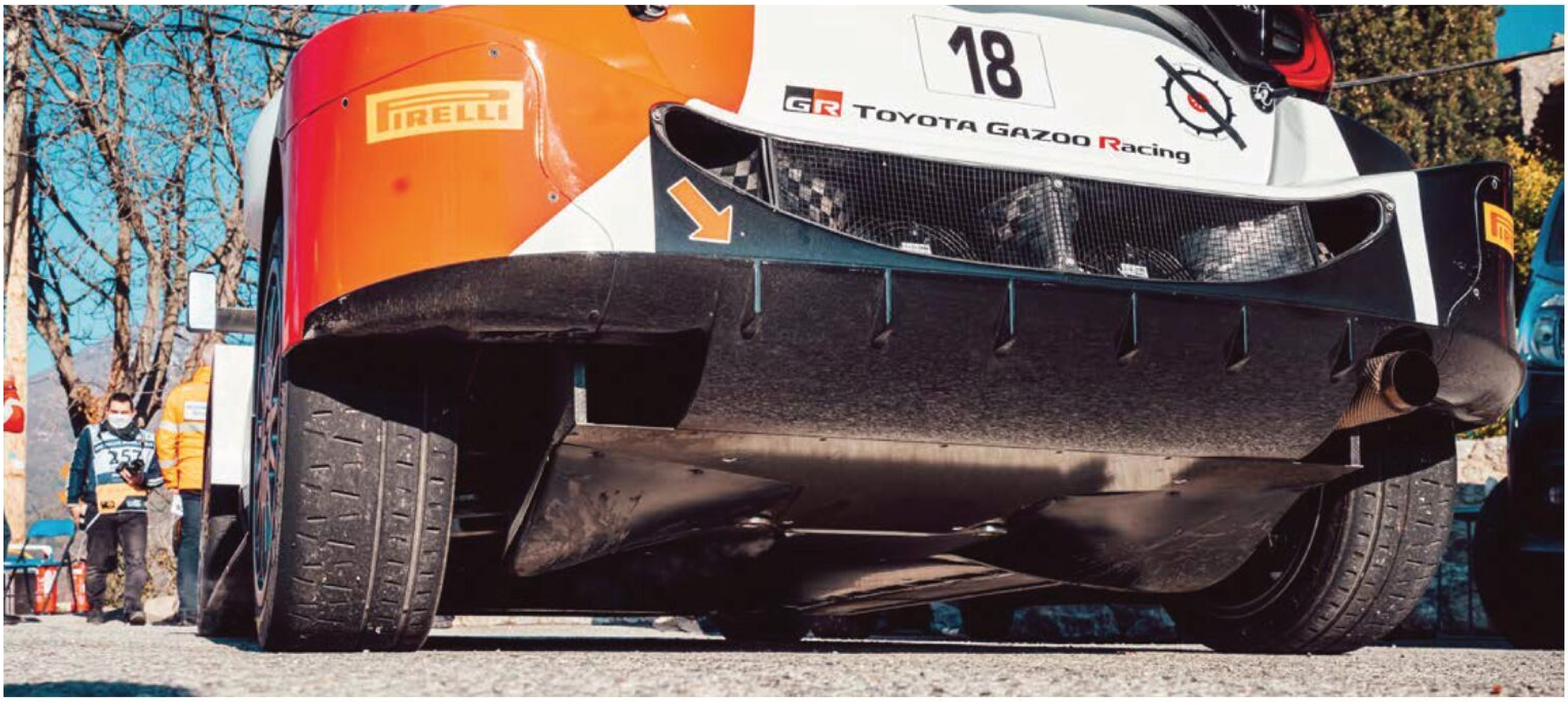
'However, you will see all of the cars are slightly different, where we've taken the regulations and adapted the architecture to how we want to best present our cars for overall performance.'

One area where there has been a notable divergence in approach is the treatment of the suspension struts, specifically, their location in relation to the axle centrelines. Since at least 2017, both M-Sport and Toyota have offset their suspension struts relative to the axle line, allowing for a longer damper with greater travel. Hyundai, on the other hand, stuck with mounting its dampers in line with the axle. For 2021, the situation was reversed, M-Sport and


Lawrence Butcher

The intricate engine bay ducting previously used to drive airflow over the cars' outer surfaces has now been banned, so cooling packages for the largely unchanged, 1.6-litre, turbocharged, inline four-cylinder engines required extensive re-development


Lawrence Butcher



Dan Bathie

Clearly, aerodynamics are still a critical design element, but the outrageous dive planes, louvres and diffusers of the previous generation WRCs are now gone, replaced by less potent solutions

Toyota placing them in line, Hyundai going for quite an extreme offset.

When asked about Toyota's approach, Fowler explains how things changed once travel was limited to 270mm (it was previously unlimited, with at least Toyota and M-Sport running well over 300mm). 'One of the first questions our suspension design team was asked to answer during the very early concept stages was, 'Okay, we're going to limit the travel to roughly x, can you fit a strut on top of the driveshaft without offsetting it, and still have the maximum travel?' After some work, the answer was yes. So that's where it went.'

The cars are capable of fully electric operation, which must be used on certain non-competitive stages of each rally, with a range of 20km possible

Hyundai's deputy team principal, Julien Moncet, remains tight lipped about his team's choice, saying only that it was as a result of the new regulations. However, Fowler was candid when asked for his opinion on the competitions' approach: 'When we first saw their homologation papers, we were a bit surprised. But suspension design and kinematics is an area of motorsport that some people have very strong opinions about, for whatever the reasons might be.'

Hybrid development

On the surface it would be easy to assume that the hybrid systems, being spec units, would not offer teams much room for development. But after a great deal of bartering when the regulations were being hammered out – at one point it seemed the FIA would mandate spec deployment strategies as well – teams have retained considerable scope to tailor the energy deployment and regen' from the 100kW system.

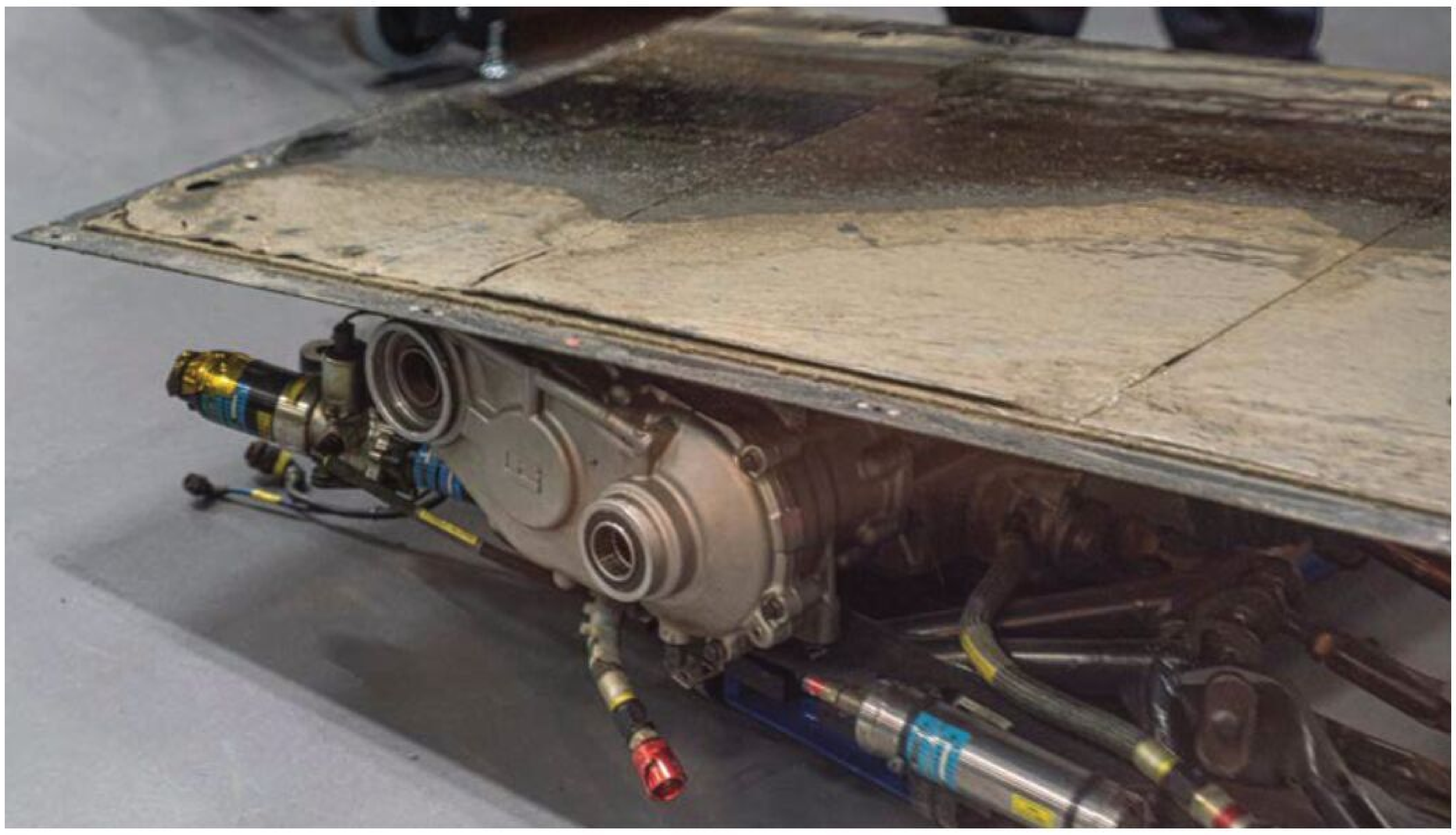
Developed by Compact Dynamics, a subsidiary of Schaeffler, the hybrid takes the form of a single, drop-in unit, encapsulated within what is effectively a ballistic box holding the motor, inverter and battery. The only external connections are for the liquid cooling circuits for the motor, inverter and battery, the latter supplied by Austria-based Kreisel, and using direct fluid cooling of the individual cells. Plus the charging system.

The cars are capable of fully electric operation, which must be used on certain non-competitive stages of each rally, with a range of 20km possible.

As soon as the first development hybrid units reached teams, they were keen to characterise them and start developing control strategies, as Williams recalls: 'The very first thing we did was take the unit and put it on the dyno, to be sure we could control it, calibrate it and have a good set up before we go anywhere near a car.

'After that, we're doing lots of work on the dyno to make sure we can control it with the strategies we want to use to get the best performance. As well as just reliability and durability testing, that kind of thing.'

The layout of the hybrid is interesting in that the motor generator is offset from the centreline of the car, with a cut out in the underside of the hybrid housing to allow the propshaft to pass from the transmission at the front of the car (attached to a largely unchanged from 2021, 1.6-litre, turbocharged in-line four) to the rear differential. Drive from the MGU is fed into the powertrain via



Lawrence Butcher

First glimpse of Hyundai's Ricardo-supplied rear differential, though currently teams are keeping exact details under lock and key

a second propshaft, connecting to the rear differential offset to the main propshaft.

Teams kept their rear differentials under tight wraps in Monaco, but it was possible to gain a glimpse *(see p61)* of Hyundai's Ricardo-produced unit when Ott Tänak's car retired from the rally for other reasons, but the damage left the part exposed.

Added complexity

Feeding power from the MGU into the rear differential, and in turn the entire four-wheel-drive system, meant achieving consistent behaviour in the driveline was a fiendishly complex task. This is both a mechanical issue and one of mapping, while also dictating packaging at the rear of the car.

Fowler explains: 'I think we had about 10 different solutions for this. We had a lot of options, because it affects a huge number of things. Fuel tank volume being one of them, as well as the c of g related to your tank.

'The rear suspension packaging also really depends on how you manage to get a rear differential, a small gearbox to adjust the ratio from the motor with a drop gear and two propshafts into that space.

'It was something that had to be decided early on, and was very important to the final product. So we went through it quite carefully and there were certain challenges in making sure it was efficient, both in terms of transmitting torque, but also in being small, light and in the right place.'

Beyond the packaging and mechanical design challenges, there remained the tricky matter of mapping power delivery from the MGU. And, just as importantly, energy regeneration under braking. If there is one thing a rally car must be, it's consistent. With conditions, and sometimes even surfaces, changing from corner to corner, drivers must be confident their throttle and brake inputs will translate to the same response from the car every time. With in the region of 500bhp on tap with the MGU and IC engine at full blast, the new cars are capable of catching even the sharpest driver out.

Each manufacturer is permitted to homologate three deployment and three regen' maps, shared across all of their drivers, which are then fixed until the next homologation window. These must work on tarmac *and* gravel stages, *and* suit a variety of different driving styles. Maps can be switched between stages, but not during.

For some, mapping was clearly still a work in progress on the Monte. Toyota driver, Sebastien Ogier, commented that his Yaris was not entirely to his liking after tackling mixed stages of ice and dry tarmac on the second day of running: 'It is not compromising me in every section. There are some profiles where it is fine and some where I struggle.'

Lawrence Butcher

Due to strict FIA regulations on aero packages, another big challenge for manufacturers has been cooling the rear-mounted MGU

Lawrence Butcher

With the MGU feeding power into the rear differential via a small additional gearbox, rear suspension packaging is necessarily tight

For Toyota, development of its maps has been, and continues to be, a complex affair, encompassing simulation, bench testing and track testing using torque sensors to gather data. Fowler: 'We've done quite a lot of work on it, because it presented some fundamental dynamic problems we needed to solve. It's certainly an area that needs to be developed further still.'

Aero restraint

If an entirely new chassis, and the introduction of hybrid power, was not enough for teams to contend with, the aerodynamic regulations have also come in for a shake up. In the name of cost control, the considerable freedoms dished out in 2017 have been reined in.

Each manufacturer is permitted to homologate three deployment and three regen' maps, shared across all of their drivers

Everyone agreed that the last generation of cars looked fantastic, but they were excruciatingly expensive to develop.

Toyota led the charge in 2017, with a no-holds barred approach to aero development that left the Yaris looking like the TS050 LMP1's stunted love child.

Fowler acknowledges the team left no potential performance avenue unexplored: 'What happens with aerodynamics in WRC – I mean, from engineering point of view, we enjoyed it – but it was a bit silly.'

He also happily takes responsibility for the development battle that ensued. 'Probably a big proportion of the fault lies in our design office. Maybe too many late nights or something. But certainly, when we drew a line in the sand at Monte Carlo 2017, the rest said, 'okay, they're doing something there.'

'I think that fired them up. Everybody then went looking for every gain available. I think the [new] regulations going in this direction is good for everybody.'

The new rules direction has seen much of the spectacle of the old cars retained, but complex elements such as dive planes, wheelarch louvres and diffusers are now banned, as is the intricate duct work under the bonnets, used to fine tune airflow over the outer bodywork. Aerodynamics are still important, but the sum total of the bodywork additions is less potent now than before.

'The FIA have been fairly forceful, let's say, pushing the aero in the direction they want'

Chris Williams, technical director at M-Sport

Fowler does, however, caution that when rules become more restrictive, they are also harder to police. 'When you don't have laws, or very few, simple laws, you can easily monitor what's going on. But when you have very strict rules, in order to keep the integrity of them, you have to police them strongly.'

This has changed the relationship between teams and the FIA. Fowler explains: 'One of the things with how we deal with aerodynamics with the FIA, which differed from the previous, is that we have been sharing 3D CAD with them for many months. Showing them our planned homologation bodywork and then getting feedback about whether it complies with the rules or not.'

Surface constraints

On this last point, all three manufacturers' initial stabs at bodywork fell foul of what the FIA envisaged, so they were told to go back and try again. 'We've been constrained on surface shape,' says Williams. 'We had some quite dramatic surface shapes at one point, but were deemed to not really be adhering to the regulations, so some had to be removed. It's been quite strict in certain areas. The FIA have been fairly forceful, let's say, pushing the aero in the direction they want. Anything that was even marginally in the grey area has been removed. So you will see the cars' look in certain areas is very similar.'

One particularly challenging aspect for the teams, related to both the aero package and hybrid system, was cooling the latter. Looking across the service park,

Aerodynamics are still important, but the sum total of the bodywork additions is less potent now than before

considerable variation in elements such as cooling scoops on the rear quarters and their associate internal ducting were to be seen. Fowler notes that initially, his engineering team did not think it would be possible to incorporate sufficient cooling capacity, within the constraints of the rules, to accommodate they hybrid's needs across all rally conditions. However, after an intense development programme in both the virtual and physical domains, he feels they have reached around 95 per cent of the capacity required.

One final point on the aerodynamics of the new cars was also raised by Fowler. With fewer toys to play with, the relative gains to be made from finding an improvement in any area should be higher than before. This applies across the whole car, and although they are less extreme than before, there will be no let up in development any time soon.

With M-Sport and Toyota seemingly evenly matched out of the blocks, and Hyundai having to play catch up, rallying's new era shows promise, particularly if the rules revamp can succeed in attracting a new manufacturer or two.

Ricardo in Rally1

As a company, Ricardo has a long history in the World Rally Championship. Stemming from research into the benefits of all-wheel drive and the development of the viscous coupling through the middle of the last century, Group B was a landmark change in the use of both technologies in rallying and Ricardo has been involved in this competitive arena ever since.

When the regulations for a series change, it's normally the best time to try and gain a competitive advantage. The change to the new Rally1 regulations for 2022 has allowed Ricardo to leverage technologies from several different competitive arenas to try and develop the most competitive R1 driveline possible.

Working with a long-established partner is also a valuable step in reducing development issues. Avenues of communication are already well established, and the cross-company teams have the same frames of reference from existing programmes.

It is this background that led Hyundai Motorsport GmbH (HMSG) and Ricardo to come together to develop a new driveline for the Hyundai i20 N Rally1. The intention was to use some of the rally-proven components from their existing joint venture, the Ricardo driveline fitted to the Hyundai i20 R5. Refinements were planned to be introduced based on experiences from WRC and Formula E.

With the emphasis on cost reduction, semi-automatic gearshifts and centre differentials are now forbidden in the new Rally1 regulations. This prompted the use of technologies taken directly from the R5 product, namely the manual gearshift arrangement and its associated technologies in the gearbox, and the handbrake disconnect function in the rear axle.

Damage limitation

For Rally1, however, the partnership has continued to develop the gearshift to further reduce shifting loads in comparison to the R5 unit. Having stepped back from a semi-automatic 'shift, the risk of gearbox (and engine) damage with a missed manual shift has increased substantially, and anything that can be done to offset this is critical.

The handbrake disconnect unit has also seen some refinements over the R5 version. This is to ensure a more consistent operation in Rally1 with the increased torque the unit sees in that application, and to allow adaptions to add the hybrid drive to the rear axle. Ricardo has employed learnings from their success in Formula E here to help with this installation.

The hybrid drive gear train in Rally1 is restricted by regulation, meaning the ultimate solution for these components is somewhat compromised by the rules concerning gear face width, casing wall thickness and minimum axle weight.

The World Rally Championship, by definition, rallies all over the globe. No other discipline sees the variety of conditions a Rally1 car will see throughout a season of competition. This means that an ultimate solution needs the very best in drivetrain engineering to ensure performance and reliability, whilst complying with the new regulations. Taking lessons learnt from an existing, reliable product and adding refinements from other programmes to suit this revised application is what Hyundai Motorsport and Ricardo have been working towards throughout the joint development of this new driveline. Results during the new season will hopefully verify this philosophy.

'We've partnered with Hyundai Motorsport in R5 for a number of seasons now and it's fantastic to extend this working relationship to include the Hyundai i20 N Rally1,' says Steve Blevins, head of engineering at Ricardo's Performance Products team. 'We announced our technical partnership with Hyundai Motorsport for all their four-wheel drive drivelines in April 2021 and this programme is the latest manifestation of this. Collectively, we've decades of experience between us and we're hoping this will ultimately be reflected in the performance of the driveline in competition through the 2022 season and beyond.'


HYUNDAI
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Control freaks

Understanding the technology of dampers and the science behind their ongoing development

By JAHEE CAMPBELL-BRENNAN

In mechanical systems, vibrations and oscillations occurring due to external energy inputs are an inevitable reality. Thankfully, through a multitude of physical phenomena, this kinetic energy is converted into heat and sound energy. If this fundamental process didn't occur, our world would be a very different, and resonating place.

Viscous damping is one such process that sees kinetic energy dissipated through the friction generated by the relative movement of molecules within a fluid medium.

Within powertrain components such as gearboxes, such processes are considered parasitic – a source of inefficiency we would like to do without – but one area in which we do harness viscous damping to our advantage is in the suspension system.

To a racecar, the suspension system's main objectives are to manage weight transfer around the chassis and to control energy input from the road into the unsprung mass to manage variation in contact pressure at the tyre / track interface.

As the inherent structural damping within the metallic road spring is hugely insufficient in this application, the suspension system must employ methods through which to provide additional damping to control the oscillations of the sprung mass. By utilising viscous principles to provide a damping force proportional to the input velocity, modern automotive dampers do exactly this.

As the wheel moves relative to the body and the damper is displaced, oil is forced to flow through a series of small orifices and valves within the damper. The shearing stresses that result from this motion are resisted through intermolecular forces to generate an opposing force to dissipate these oscillations with an exponential decay.

A measure of the strength of these intermolecular forces is via the viscosity. More viscous oils demonstrate a stronger resistance to this flow, and damper oil is generally specified with a viscosity of between 10-20cSt (centistokes). For comparison, olive oil at room temperature is around 85cSt, so damper oil is relatively thin.

Modern, high-performance dampers have essentially converged on two main solutions: monotube and twin-tube concepts. These operate on the same basic principles but through different architectures, making each more suitable to certain applications than others.

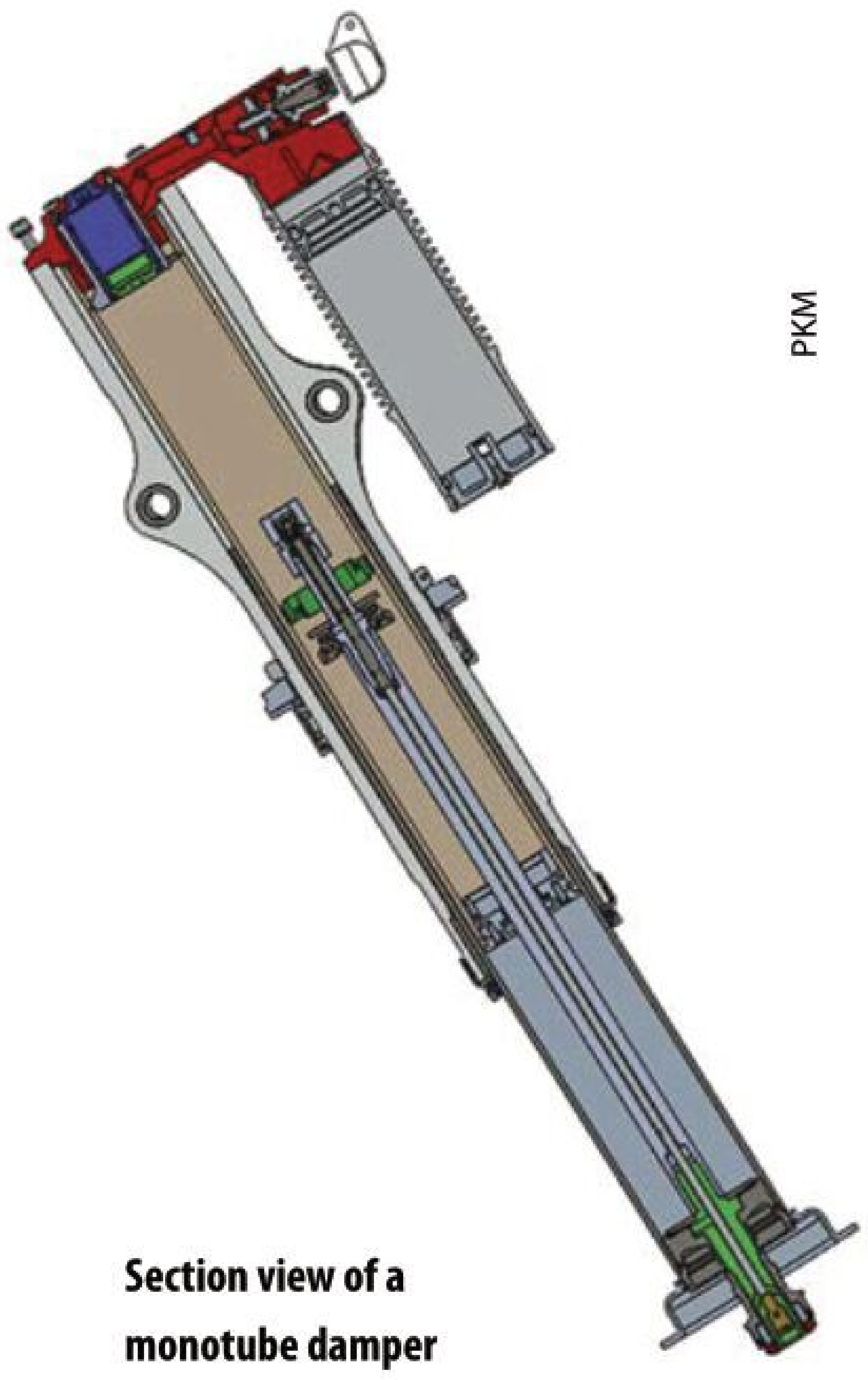
Monotube dampers

The mechanically more straightforward monotube damper architecture encloses the working cylinder of the damper in a single layered 'tube' containing the oil.

As the wheel moves relative to the chassis due to driver or road inputs, a piston attached to the end of the input shaft is forced through the oil, causing it to flow under high pressure and high speed past various orifices and shim plates housed within the piston that provide resistance.

PKM

PKM's P30 LMP2 twin-tube damper, as used in ORECA, Dallara and Ligier chassis



Section view of a monotube damper

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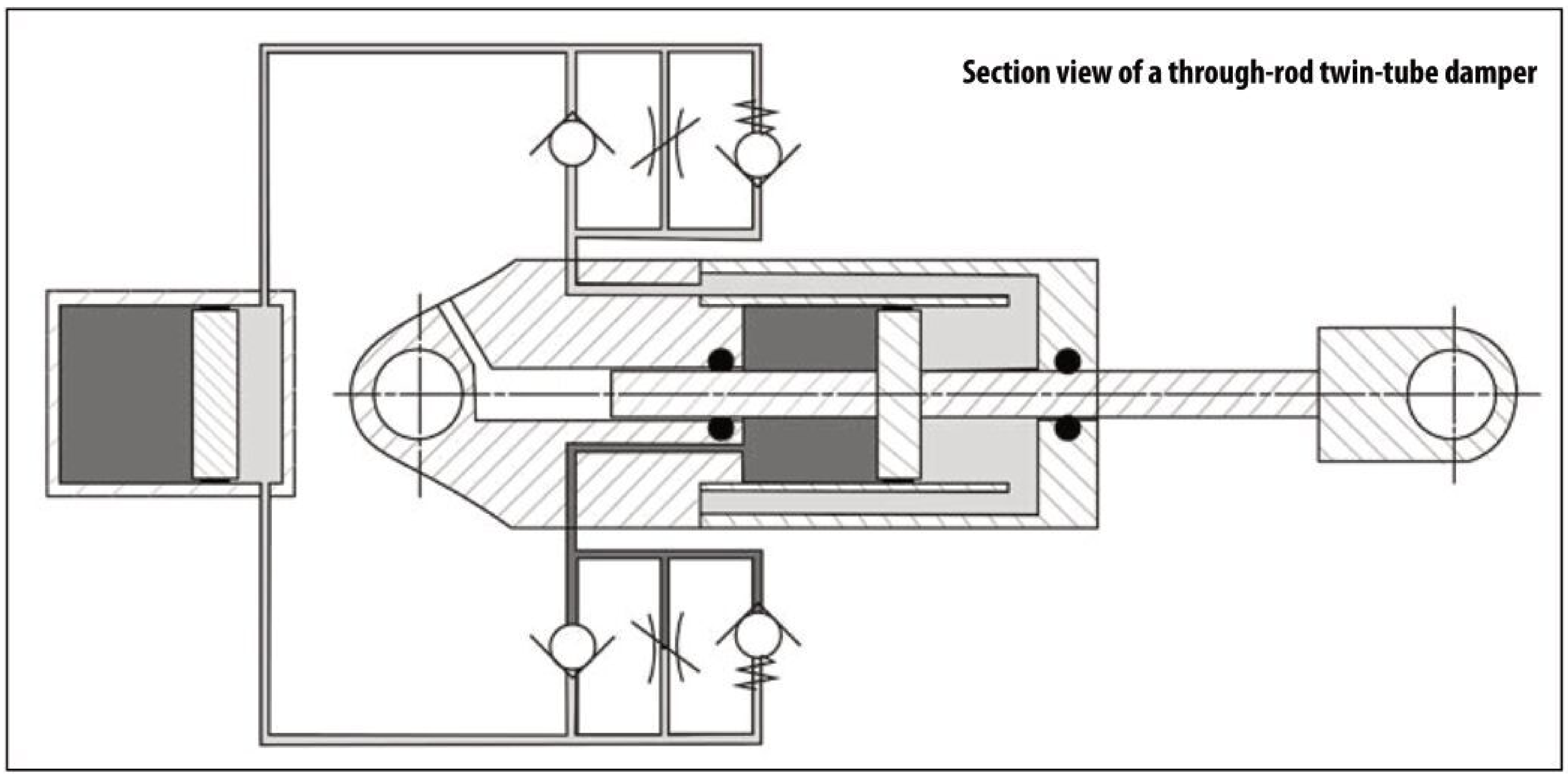

Section view of a through-rod twin-tube damper

Öhlins

The piston is sealed against the internal diameter of the cylinder to prevent oil bypassing the valving and damper forces are modulated by adjusting the sizes and opening pressures of the orifices and various shim plates present.

An important, fundamental concept to understand about traditional damper architectures is that because the piston is connected to the damper shaft on one side only, the volume of the shaft in the working cylinder at full compression displaces a larger volume of oil than in full rebound.

As a solution to manage this, more advanced monotube dampers feature an external fluid reservoir to provide a volume for the displaced oil. Flow into the reservoir can also be controlled by a valve.

On the rebound stroke, the high forces generated by fast wheel movements can cause very low pressure in the downstream side of the piston. If the pressure within the damper fluid falls below the vapour pressure, cavitation occurs as bubbles of vapour form, and subsequently burst as pressure rises again. This is detrimental on two fronts. It can cause damage to adjacent components by creating shockwaves, and it also introduces additional compressibility into the damper fluid, which dramatically changes its performance.

To maintain a minimum pressure within the fluid and hold off cavitation, expansion reservoirs in monotube dampers feature a nitrogen gas volume pressurised at up to 20bar and separated from the oil by a diaphragm to exert a positive pressure on the oil.

Twin-tube dampers

Twin-tube dampers work in much the same way as monotubes. The key differentiator is the main cylinder of the damper is 'sleeved' by an additional outer cylinder, which leads to a different valving philosophy.

In twin tubes, the piston is often solid so, instead of providing the valving, it serves only as a mechanism of pumping fluid through valves located elsewhere on the fluid circuit. The secondary outer tube is present to provide the rebound volume with a flow path into this valving as fluid is pumped around during damper travel.

By freeing the piston of its valving obligations, twin tubes can offer the advantages of greater control of the damper's response. The lower pressure differentials resulting from this approach also reduce the propensity of the damper for cavitation.

'If you reduce the risk of cavitation in the dampers, it means you're able to run a lower nose (inflation) pressure,' explains Paul-Etienne Berthe, co-founder and chief of design at PKM, a company who produce motorsport dampers, specialising in LMP platforms. 'For example, with twin-tube dampers you can run 5bar or less nose pressure, while you need around 20bar with standard monotube systems. This means you can have a much lower pre-load on the seals and reduced friction.'

The asymmetries in volumes displaced by each stroke of the piston in traditional monotube and twin-tube systems is always sub optimal. The additional fluid displaced in compression increases the oil volume in the reservoir, which means the gas volume must compress. In this process, the movement of the diaphragm introduces additional friction and resistance to compression movement.

Friction is detrimental to the damper for its influence into initial response, where subjectively it's experienced as 'harsh' quality. This is not preferential for either tyre grip or tyre life as it increases the energy into the tyre. Less friction is always better.

Because of this, the twin-tube concept has been further developed to feature what's commonly referred to as a through-rod design, in which the damper shaft extends through the piston and right to the top of the working oil volume. With this architecture, the same volume of fluid is maintained in the cylinder at all points in the damper's operation.

By displacing equal volumes of fluid in each section of the cylinder, the pressure drop either side of the piston is minimised. And because the gas volume is not disturbed, friction introduced by diaphragm movement is eliminated.

'With our TTX twin-tube designs, the valves can be small compared to the piston diameter, and a lot of oil is moved at a high speed, which is great for flow control. This is beneficial with cars using pushrods where a quick response is needed,' notes Jonas Jarlmark Näfver, senior manager of mechatronics and vehicle performance at Öhlins. 'We use both monotube and twin-tube dampers, depending on what we are trying to achieve and what traits the vehicle is more in need of.'

Generally, monotubes are preferable where low compression forces and lower adjustability is needed, while twin-tube designs are preferable where compression forces are high and more adjustability a requirement.

Damper tuning

Regardless of the chosen architecture, to tune the damping for an optimal response over the working speed range, motorsport dampers have adjustable valving, which in twin-tube designs generally comprises a mixture of needle and poppet valves.

The response of motorsport dampers is divided into two discrete operating regions – the high-speed region and the low-speed region.

If the pressure within the damper fluid falls below the vapour pressure, cavitation occurs as bubbles of vapour form, and subsequently burst as pressure rises again

XPB

Aston Martin Racing

Low-speed damping – generally occurring at speeds less than 0.1m/s – is associated with a 'crisp' turn-in response, as this PKM-equipped Oreca 07 Le Mans Prototype shows

Kerb strikes, characterised by violent, high speed damper input, need special treatment. Blow-off valves do the trick, as this Aston Martin with Öhlins dampers proved at Le Mans

High-end dampers provide a customisable damping response over five distinct speed ranges: low-speed compression and rebound, high-speed compression and rebound and the 'blow-off' range applying to super high-speed compression inputs.

Low-speed damping generally applies at speeds <0.1m/s and is associated with controlling the motion of the body in response to driver inputs. It's important to the perceived driver feel of the car, and also the rate of loading of the tyres during weight transfer.

Conversely, high-speed damping is concerned with damper speeds >0.1m/s, which is the region concerned with inputs from the track profile and control of the chassis following larger impacts such as kerb strikes. This is the region of damping with most input into the variations in contact pressure experienced at the tyre / road interface, and is very important in modulating the energy input into the tyre.

'It's easy to figure out the appropriate valving boundaries between each speed range,' says Jarlmark Näfver. 'If you have the driver just make some steering angle sweeps on track, the damper speeds you measure effectively define the low-speed range, while anything above this is due to road profile and kerbs, and falls in the high-speed range.'

The blow-off range comes into play in very high-speed inputs such as kerb strikes. Without a distinct damper response for this range, the damping forces would be extremely high and a lot of energy would be communicated into the chassis, unsettling the car.

'We use blow-off valves on our dampers where we expect quite significant kerb strikes, essentially on real high velocity and high amplitude inputs. Their function is to rapidly drop off the damping force where it's not needed and allow the wheel to conform to the kerb,' continues Jarlmark Näfver.

The response of a particular damper is quantified using a piece of equipment called a damper dynamometer, which subjects it to a range of input speeds and measures the magnitude of the force it generates. The data from these machines is provided in terms of a force vs velocity (F-V) curve.

Damper response

The ideal damper response in terms of the forces generated within each speed range, or damper curve, varies for different applications, and is based on the high and low-speed damping requirements of the individual car at a particular track.

The interaction of forces across the damper speed range produces either a digressive curve (**Figure 1**), where the gradient trends to decrease with increasing velocity, a progressive curve (**Figure 2**), in which the gradient trends to increase with increasing velocity or a linear 'curve', which maintains the same gradient across the speed range.

The masses and inertias seen in circuit-based racecars, combined with high lateral

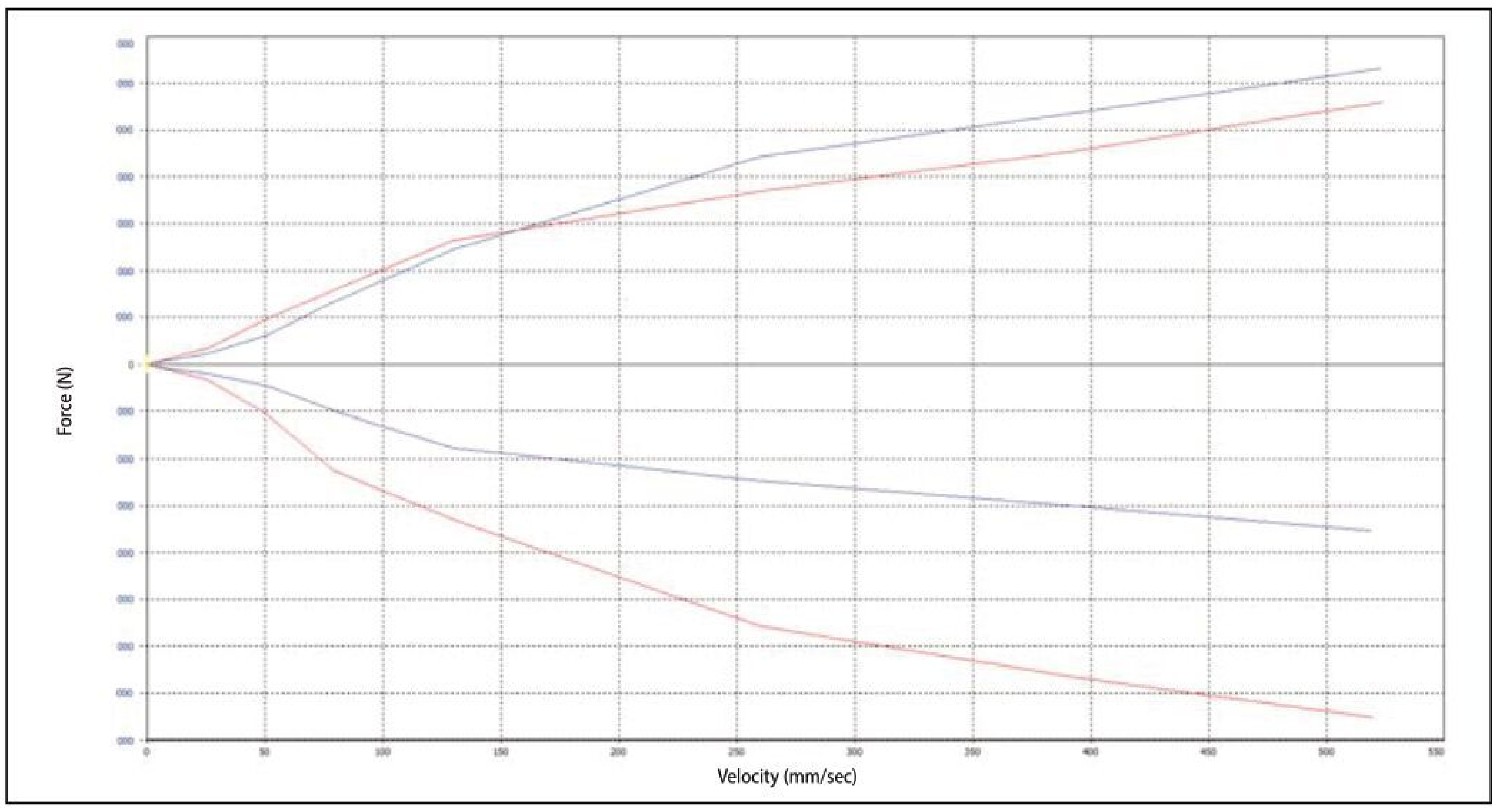

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Fig 1: F-V curve of a digressive, track-based damping set-up

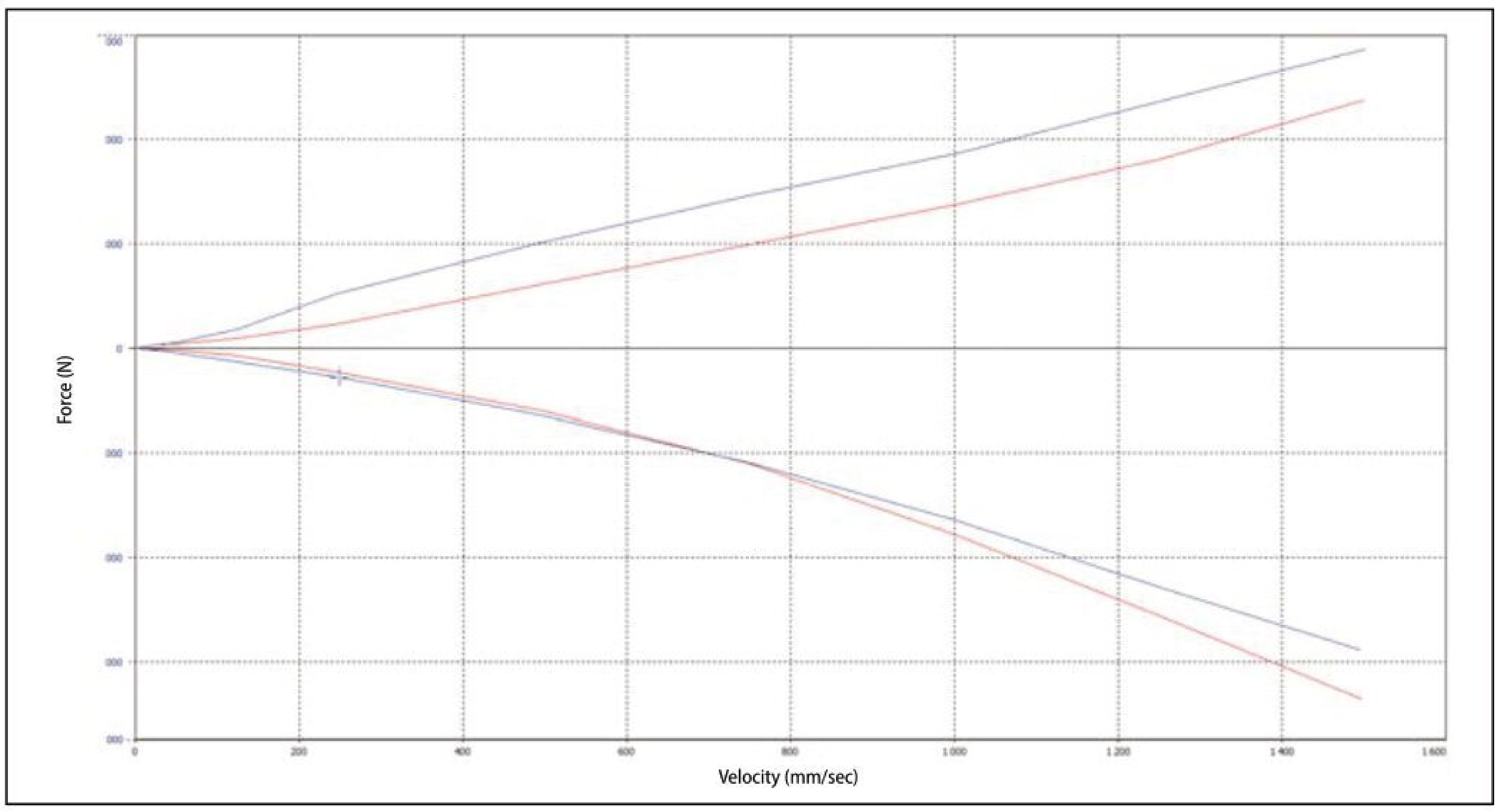

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Fig 2: F-V curve of a progressive, track-based damping set-up, more likely seen in rally and off-road applications

accelerations and smooth track surfaces, generally dictate a high amount of low-speed damping to control the body and a relatively more constant high-speed damping force. This produces a digressive curve.

Off-road racing, on the other hand, where the forces are lower, requires less low-speed damping and a supple suspension at mid-speed inputs to absorb higher amplitude bumps, but a high force to adequately absorb jump impacts and other excursions. This generally results in a progressive curve.

The different masses and inertias involved in compression and rebound also drive asymmetric damping requirements, so the valving requirements differ in magnitude for each direction of travel. Regardless of the specifics, it's important the damper dissipates equal amounts of energy in rebound and compression, so the target is to ensure this condition is maintained as much as possible.

Bump stops

With the mass of the vehicle, at the extremes of compression travel the force with which the damper bottoms out at the end of its travel can be significant, especially landing from jumps and passing over kerbs. To protect the damper itself, and introduce some element of response control in this range of operation, dampers use bump stops.

In circuit racing applications, these are simple elastomer parts that sit at the bottom of the damper shaft. Once engaged, their spring rate is very non-linear and rises sharply to provide the required deceleration. Bump stops can be selected with different rates dependent on the magnitude of engagement seen at particular circuits, but they also serve an important function for the aerodynamic platform.

In high aero categories, such as the old LMP1 era of the WEC pictured here, bump stops provide a method of maintaining a car's minimum ride height when travelling at high speed, while at the same time allowing the use of soft springs for low-speed grip

'As a general principle, we always try to keep our dampers out of the bump rubbers as they add a lot of non-linearity and, by relying on them to generate chassis performance, you're losing grip,' explains Jarlmark Näfver. 'If you need the chassis control and can sacrifice some ultimate grip, as is the case with high aero cars in LMP and Formula 1, for examples, the bump stops do serve an additional function.'

The spring rates required of a system to support a chassis at the correct ride height, with thousands of kg of aero load at the end of the Mulsanne Straight at Le Mans, for example, would compromise grip levels in the low-speed section of the tracks significantly. Using the bump stops as a method of limiting wheel travel and maintaining ride height when the aero load overwhelms the road spring in this manner is therefore very useful, and allows the use of softer road spring rates for best tyre grip.

'At Daytona, for example, we even use asymmetrical bump stops,' adds Thierry Gravier, another co-founder of PKM. 'The car travels through some very high-speed, high-*g*, banked curves where it can experience a large amount of body roll. This is a bad situation for the aero platform, so to keep the underside of the car parallel with the track we use asymmetrical stops left to right to limit the roll angle at key corners.'

'If you need the chassis control and can sacrifice some ultimate grip, as is the case with high aero cars in LMP and Formula 1, the bump stops do serve an additional function'

Jonas Jarlmark Näfver, senior manager of mechatronics and vehicle performance at Öhlins

In off-road and rally dampers, the extremely high damper velocities seen following jump landings and other high amplitude compressive inputs provide a completely different set of boundary conditions for the bump stop, which requires a very different approach.

Hydraulic bump stops

In this case, hydraulic bump stops are used, which can provide as much as 50mm travel in some cases. Through their nature, the

Öhlins supplies through-rod, twin-tube dampers for the Next Generation NASCAR series

World Rally Car dampers supplied by PKM feature 300mm of travel and use hydraulic bump stops to absorb violent jump impacts


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hydraulic bump stops also allow engineers to design unique, adjustable F-V curves separate from the main damper's action. A damper within a damper if you will.

'The hydraulic bump stops are externally adjustable, which allows us to set its performance over the different stages of travel. The adjustability changes the shape of the curve to adjust the force both at the beginning, middle and end of the bump stop's range,' notes Berthe.

The performance of the bump stop in this application, interestingly, is also dependent on both velocity and displacement.

'The hydraulic bump stops in our rally dampers are actually adjusted using something more like a spool than a needle valve. This means we drill different orifices for different displacement positions, and you can have a completely different curve [digressive / progressive] for each stage of its travel,' complements Gravier.

Damper hysteresis

The viscous forces within the oil are the primary means of dissipating energy, but losses occur in many parts of the damper, including unintended flexibility within the body and other structural parts, compressibility within the damper oil and cavitation.

This form of energy dissipation always means that the energy of the compression stroke does not equal the energy of the rebound stroke. The energy dissipated within each cycle is identified as hysteresis.

The hysteresis displayed by a damper determines the phase of its response, which can either 'lag' or 'lead' the input. If the gradient of the initial force is high, this is described as a phase leading damper, the converse is described as phase lagging.

Phase is also influenced by valving behaviour so, by controlling this, damper engineers can even use phase behaviour to their advantage.

'As an example, if the phase is leading the velocity, the damper initially generates an amount of inertia that can be used to control the chassis in a similar sense as an inerter would, if you know what you're doing,' explains Jarlmark Näfver. 'In this case, the transient response time is minimised, which can tighten up turn in.'

On the other hand, a lag in phase gives a somewhat more displacement-focused initial response, as the spring provides the majority of the force in the first moments. It's a very small amount of time, just milliseconds, but the effect can be quite pronounced.

'A phase which is lagging in a controlled manner can be beneficial for rally cars over certain surfaces, such as hard gravel,' continues Jarlmark Näfver.

Control in this manner can be implemented by using valves that are slow to open, giving a very high force with only a little velocity for that initial transient period until nominal force is reached.

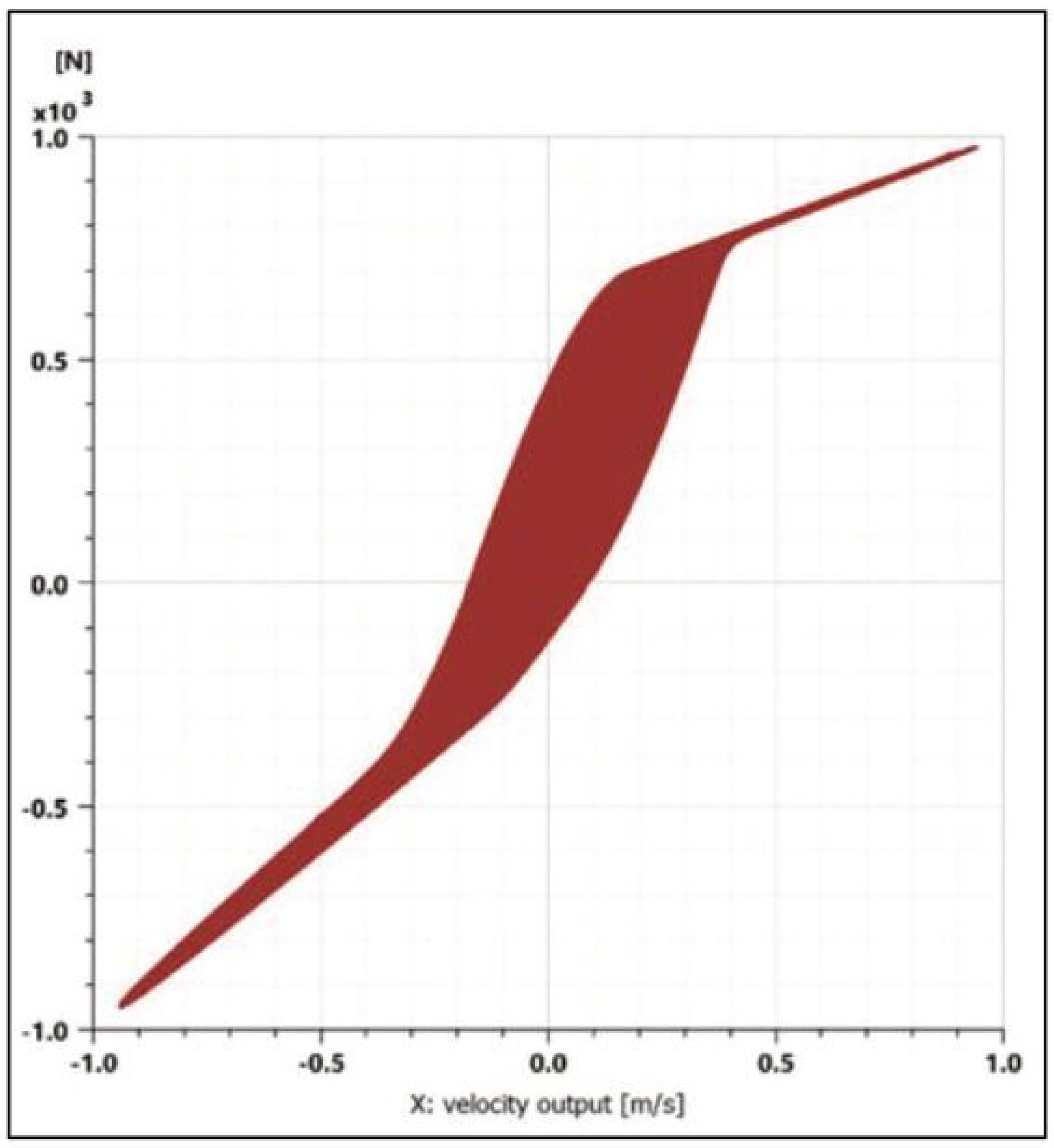
Traditionally, damper design and specification have been viewed from the outside as somewhat mysterious, with effective dampers being the result of a certain amount of trial and error, experience and, apparently, luck.

In today's engineering environment, however, simulation has pushed our understanding of the principles of fluid movement inside the damper and what we can achieve magnitudes forward.

As in many engineering disciplines, being able to rely on accurate simulation models has cut large amounts of time and expense out of the development process, in some cases enabling the prototype phase to be entirely digitised.

Development process

A logical damper development process now starts at damper specification, using software-based models to approximate the appropriate 'window' of damping required for a specific application. In order to do this, the masses, inertias, weight distributions, aerodynamic loads, inertial forces and suspension geometries must be known.



The difference in forces generated during the cycle of compression and rebound travel indicates the level of hysteresis of the damper – the red area represents the energy dissipated by the damper over the cycle

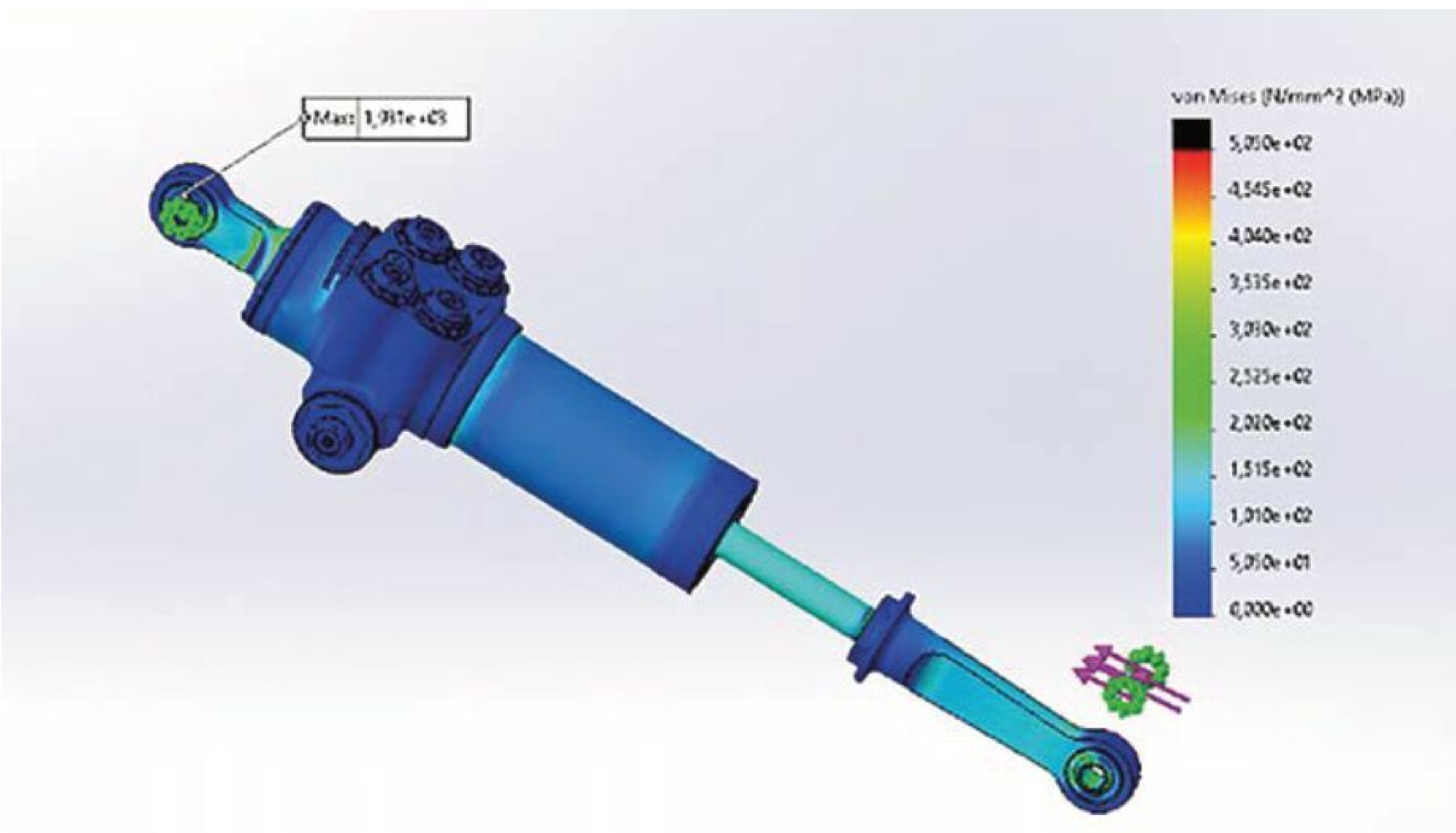
If the damper is not being developed on the drawing board alongside the vehicle, these parameters must at least be approximated before simulation can begin.

'Simulation today correlates very well with what we see on lab facilities such as the four or seven-post rig, but we also have the benefit of being able to do more. For example, we can recreate certain lateral forces and driver inputs you don't have on a shaker rig, so this is more representative of the real environment,' adds Jarlmark Näfver. 'Having the real, physical damper has been an advantage in the past, but damper modelling techniques can be so detailed that it's not an issue today.'

After validation on a damper dyno, next step is to head to the track for a first 'real' test. Simulation is not quite at the point where the real world can be modelled with complete fidelity, so track time in the physical operating environment is invaluable.

Objectives here are to verify the simulation models and that the damping values are in the correct range to give enough adjustability for the different operating conditions experienced, or even to suit a particular tyre.

Simulation has pushed our understanding of the principles of fluid movement inside the damper and what we can achieve magnitudes forward



PKM

Simulation models in recent times have driven far greater understanding in damper design and development

Where simulations are not practical or feasible, for example where the full vehicle model does not exist, there is more emphasis on lab testing to validate any assumptions made at the initial design phase. Here, the suspension shaker rig is a method of quantifying wheel loads and understanding a suspension set-up in a little more detail.

'Generally, our customers use the seven-post rig to complement their track testing, in the sense that you might be able to get 90 per cent of the way towards a set-up at the track but, to really fine tune the car within the window you found, the rigs can be great to put some numbers on the set-up options,' explains Gravier.

Environmental effects

Once performance development is finalised, the damper must prove itself over distance, so the focus then becomes about robustness and durability.

Servicing intervals of 6000km are fairly standard in motorsport dampers but, with certain endurance races running very close to this distance (5410km is the distance record set at the 2010 Le Mans 24 Hours), it's a lot to ask of the technology to maintain its performance across the full interval. Performance diminishes as oil degrades and components wear.

'The main problem for endurance races is maintaining consistent damping over the whole race. For really aggressive races, such as the Sebring 12 Hours, we can see very significant changes in damper performance over the distance. The energy going into the damper is so high, the temperatures and shearing forces just degrade the oil,' says Gravier. 'Le Mans, on the other hand, is a different challenge. It's a lot of time at full throttle and high rpm, which means a lot of vibration energy. This can be somewhat of an issue as it wears the internal valving components.'

While simulation software is an answer for much of the development process, phenomena like vibration, temperature, oil ageing and other environmental circumstances are difficult to model and are very specific to each application. This means some assessments can only be made at the track.

'The LMP2 regulations were changed some years ago and a different engine was used, which introduced a very different vibration profile into the dampers. We were finding a lot of unusual wear and in one instance the damper body was being machined by a mating part. This was quite a complex issue and resulted in a number of material and design changes,' notes Gravier. 'This is very difficult to recreate in the lab, and why track testing is still so important.'

The extreme environments seen in off-road racing take this further still. The level of energy input into a damper over a stage in the Dakar, or WRC, is really quite astonishing. Intermolecular friction is enough to heat the damper oil to well in excess of acceptable temperatures and shearing forces alone are enough to cause degradation of its properties.

'In the dampers we used to run in the Dakar rally, temperatures could sometimes reach 180degC as they're dissipating so much energy. Maintaining stable performance can get troublesome in this environment so we used to run cooling fins on the damper bodies to try and manage this,' explains Jarlmark Näfver

The immediate effect of high temperatures is the oil reduces in viscosity. To offset this, various valves within dampers can be designed such that the thermal expansion experienced works to close certain orifices, keeping the flow rate consistent and performance stable over the temperature range.

'Damper oil can expand by up to approximately eight per cent in some cases, so there must be space in the reservoir to account for this,' adds Berthe.

Modern damper oils are synthetic and internal and external sealing technologies are of a polymer construction, but much above 120degC and the lubricative properties of the oil break down, which causes high wear.

Being able to completely remove the compression damping as the wheel impacts the kerb would be very attractive, as would the ability to modulate the damping depending on the sector

It's therefore vitally important for race teams to keep on top of servicing to prevent this kind of damage occurring.

Future developments

There's no doubt digital simulations have allowed us much more insight into the physical principles involved with automotive dampers, and the biggest developments in the last decades have coincided with advancements in understandings released by simulation.

These have been capitalised upon by innovative design and advances in materials and manufacturing processes to allow better control of the damper response, but the desire for more control still burns.

Further control means damping forces can be tuned even more precisely, so much so the damper 'curves' don't have to follow a curve at all. Being able to completely remove the compression damping as the wheel impacts the kerb would be very attractive, as would the ability to modulate the damping depending on the sector, or corner, of the lap being driven.

As much as large sectors of the motorsport industry would jump at the chance to implement active damping technologies, the future of damper development very much falls on the direction of regulations, so it still looks like motor racing will be relying on the traditional hydraulic damper for some years yet.

XPB

Endurance racing pushes dampers to the limits. Their response can change dramatically from the start to the end of a long race such as the Sebring 12 Hours pictured here in 2019

Talent show

How to determine if your driver is the real deal

By DANNY NOWLAN

One of the most hotly debated questions in all of motor racing is how do you pick the drivers with talent? This is not just confined to the vehicle dynamics community. *Everyone* involved in motor racing, whether they are a punter watching on TV or an F1 team principal, has a view on this.

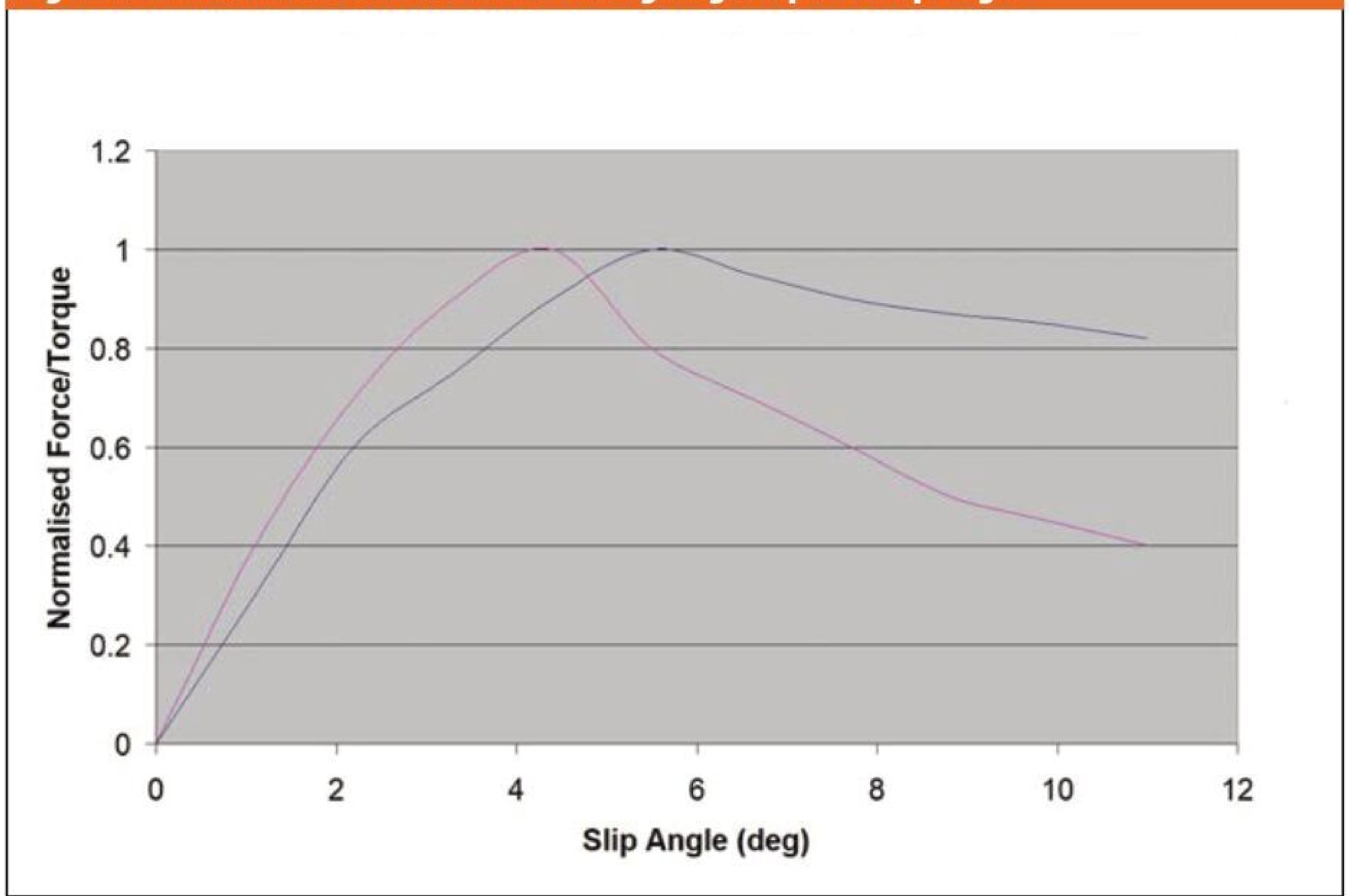
Well, lately I have been working on some projects that bring these matters into very sharp relief so, with the help of a bit of vehicle dynamics knowledge and simulation, let's take a dive into the key elements that define a driver with genuine talent, and how we can quantify this.

To kick things off in this discussion, it's worth reviewing the force vs slip angle curve and self-aligning torque vs slip angle as the relationship between these two is where the adventure starts. This is shown in **Figure 1**.

The blue trace is the slip angle curve, and the purple trace is the self-aligning torque curve. Note the gap between the peaks of both. The ability to operate within this zone of detecting when steering torque starts to get light and fuzzy is the first element that sorts the drivers with talent from those who are simply there for entertainment, or to make up the numbers. The late Carroll Smith put this rather eloquently in his book, *Drive to Win*, when he presented the graphic shown in **Figure 2**.

In theory, this should be simple to quantify but, over the last few years, two things have come up that have well and truly muddied the waters.

Fig 1: Normalised lateral force and self-aligning torque vs slip angle



Power added

The first is the addition of power steering. Okay, that's not so new. PAS in the racing sense first started to appear on Sportscars in the '90s and early 2000s, thanks to the amount of downforce they ran. It then didn't take long for it to work its way into junior formulae, and it's always been present in GT racing. The problem with prodigious amounts of power steering is it can often mask that weird, fuzzy feeling drivers feel through the steering wheel when the car is on the limit.

The second element is the widespread adoption of Driver-in-the-Loop simulation, due in part to limitations on track time. I realise this sounds counter intuitive for someone like me to say this, given DIL is a key ChassisSim selling tool, but let me go into this in more detail. Most DIL

Fig 2: The Carroll Smith breakdown of driver talent from *Drive to Win*

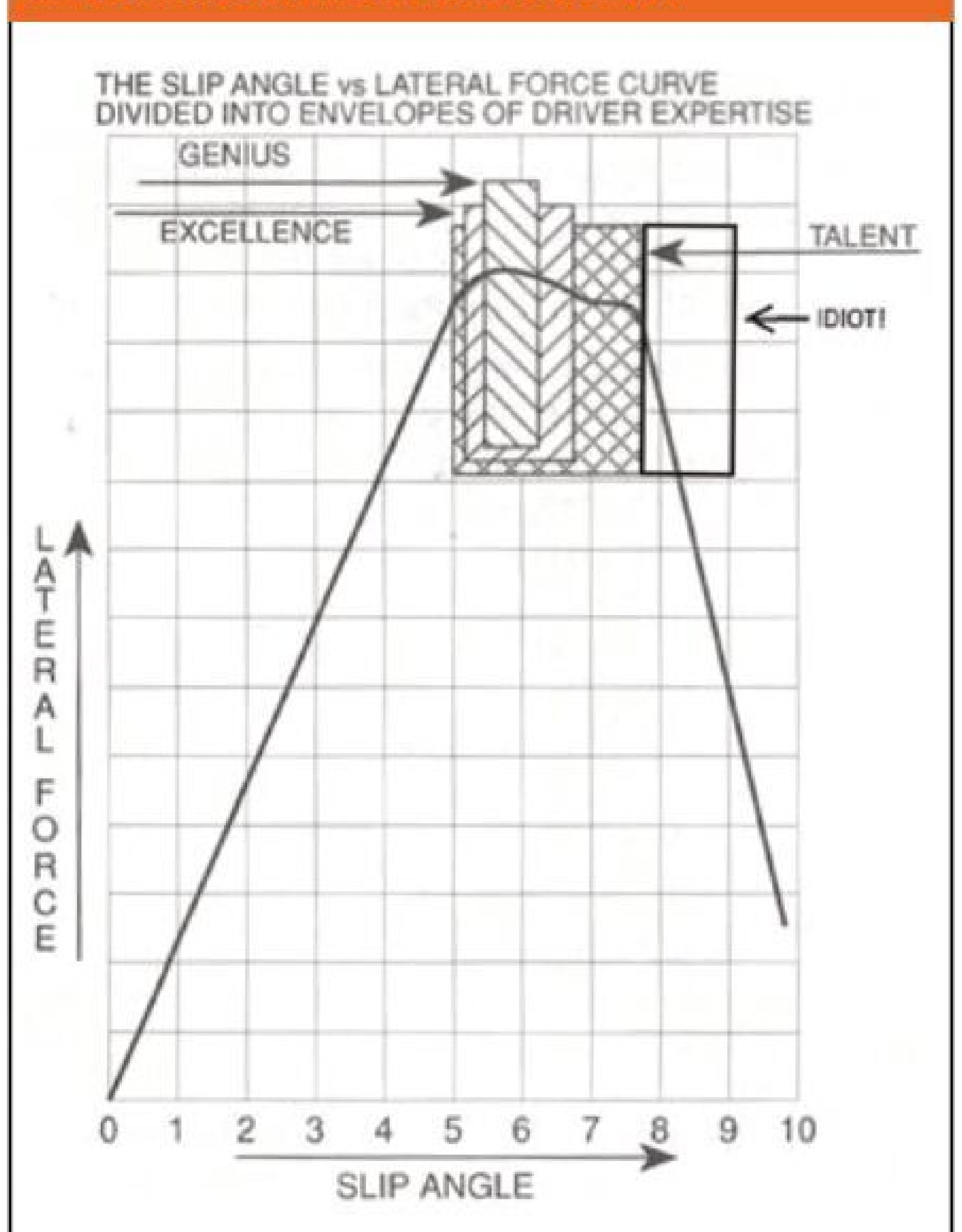
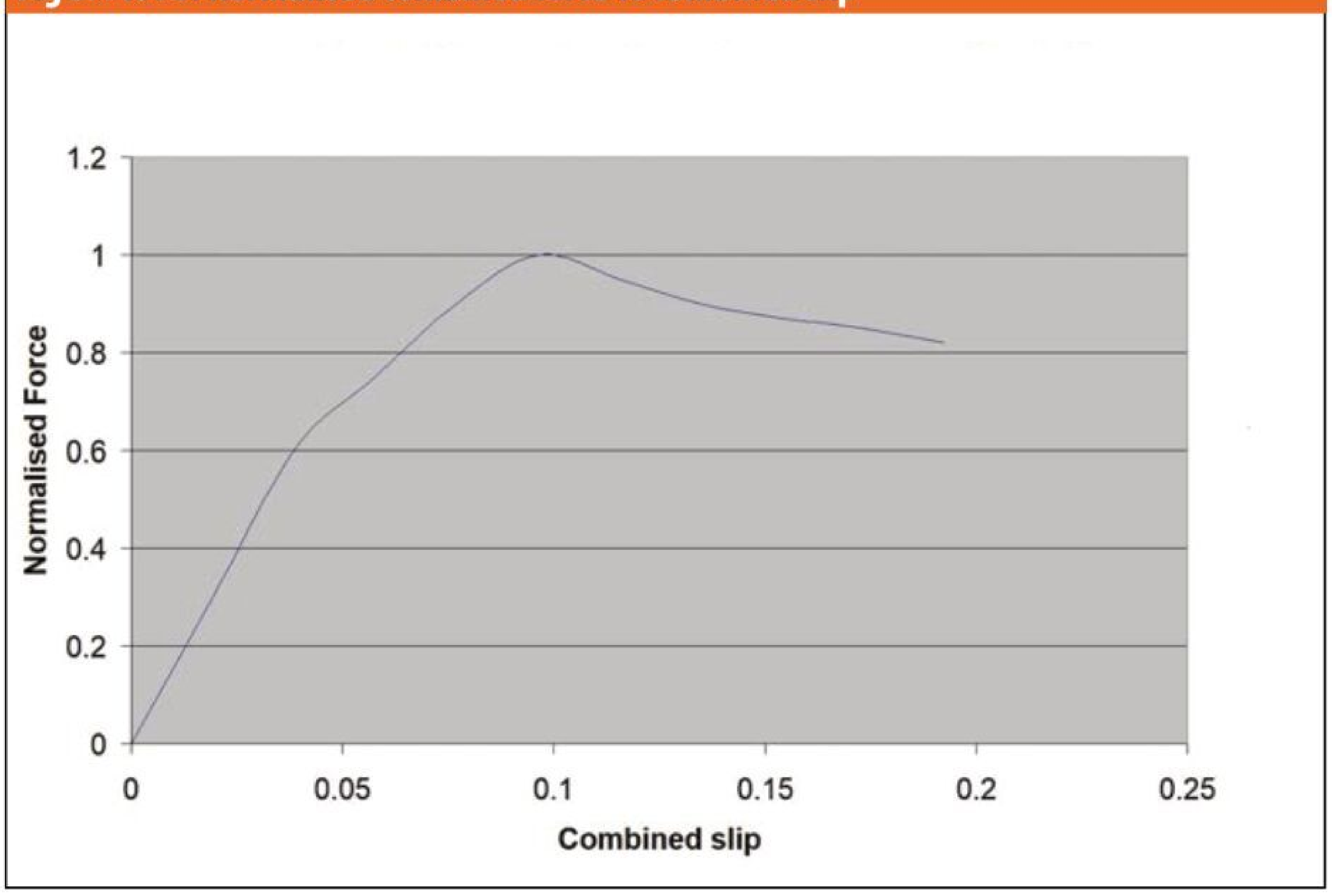


Fig 3: Plot of normalised combined force vs combined slip



software and hardware will do a pretty good job of replicating steering torque. However, it will never get it bang on the money. If this was combined with ample track time, it would not be an issue, but given the severe restrictions on track time, this key element can be overlooked. This is one of the main reasons you will never get perfect steer correlation, and we'll discuss this in further depth later.

What all these elements place a great emphasis on is feeling what the front end of the car is doing. In some respects this is where DIL simulation can be a double-edged sword. It certainly helps a driver build up the visual cues but, even with motion cueing on the simulator, it doesn't do an exact job. Again, we will discuss the ramifications of this shortly.

Traction circle

The next element to this is the driver's ability to ride the traction circle. Three-time world champion, Sir Jackie Stewart, once famously said how you take your foot *off* the brake has everything to do with the speed you will carry. To that I would further add that just as important is how you *apply* the throttle.

So, how do we quantify and visualise this? A very useful tool is combining both slip angle and slip ratio into a common parameter called combined slip, which looks something like that presented in **equation 1**.

$$comb\_slip = \sqrt{\alpha^2 + SR^2} \qquad (1)$$

Where,

$Comb\_slip$ = combined slip measurement
A = slip angle (radians)
SR = slip ratio (% / 100)

Here is where the physics gods come to our rescue. The base units for slip angle in radians and slip ratio are interchangeable. What this means if you plot this via normalised combined force is you have something like **Figure 3**.

For me, that curve is the single most important bit of the Milliken and Milliken *Race Car Vehicle Dynamics* book, and I feel acutely embarrassed that I didn't think to incorporate this into my own book, *The Dynamics of the Race Car*. However, the crucial thing to take away from the discussion here is that very good drivers can ride the combined traction conditions at the peak of the combined slip.

Fig 4a: Grip vs lateral load transfer at the front for two different tyre compounds

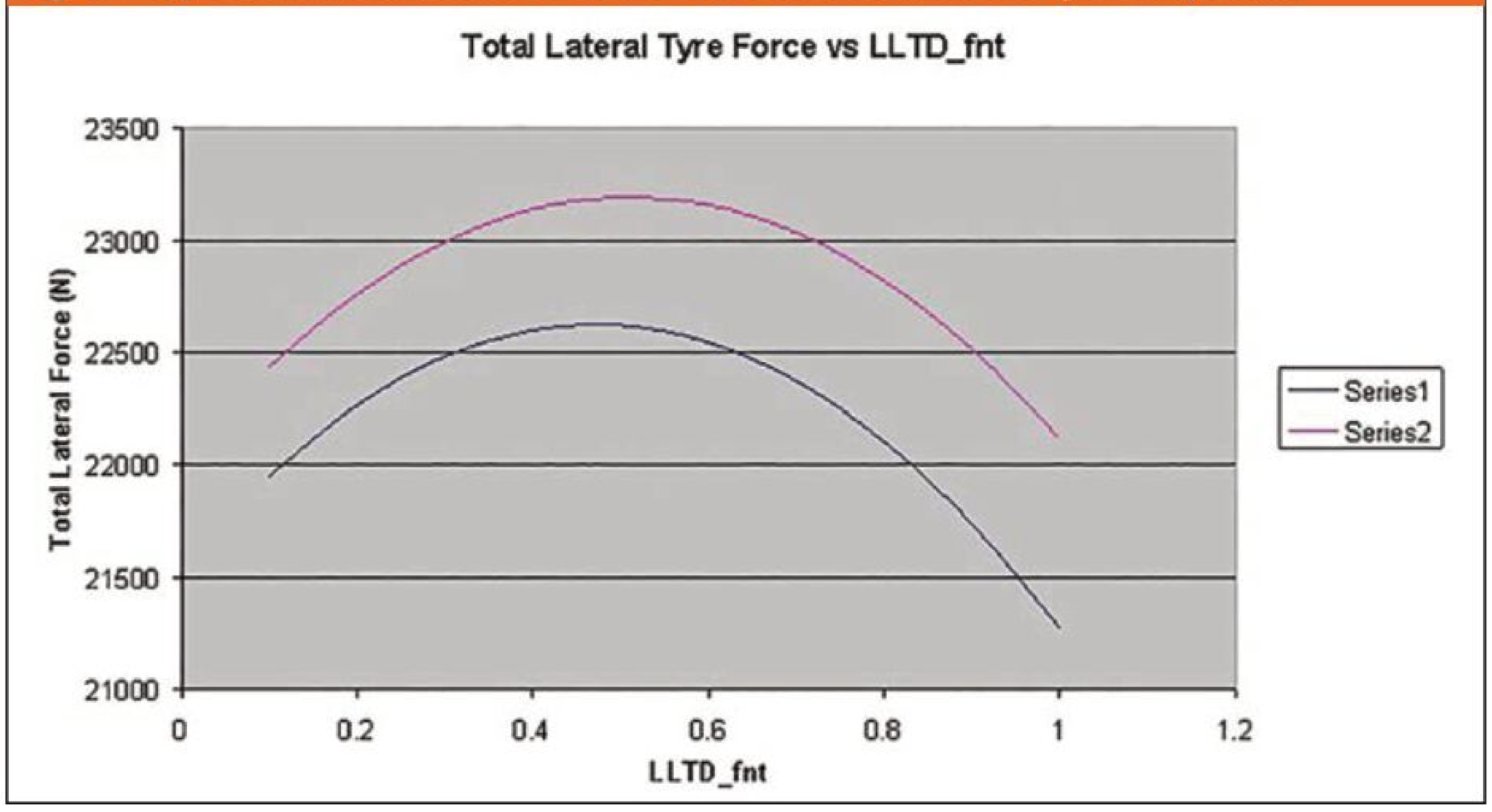
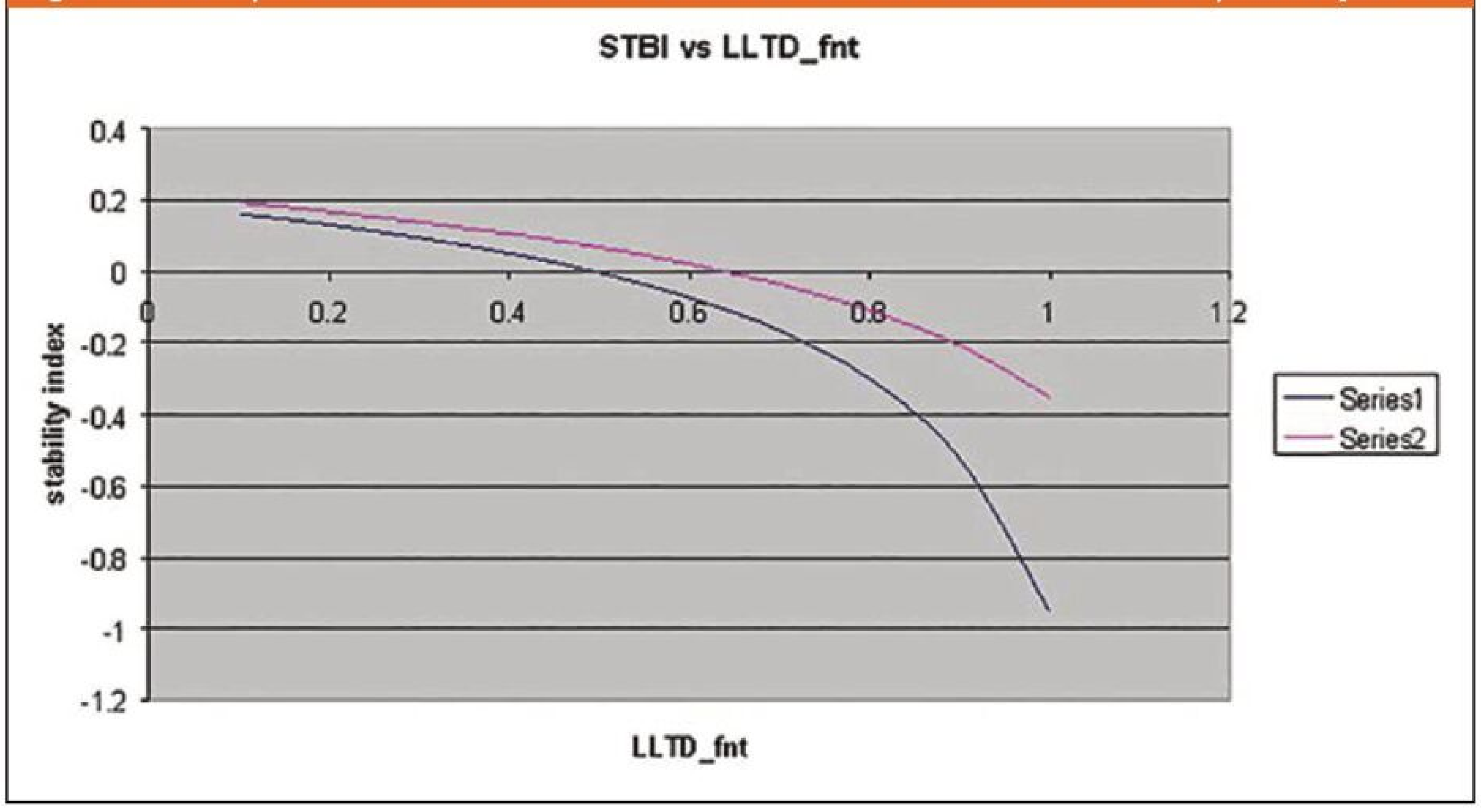


Fig 4b: Stability index vs lateral load transfer at the front for two different tyre compounds



This ability to ride on the peak of combined slip is the key separator between good amateur drivers and the really good professionals. In order to do this, you need to have an innate feeling for the tyre, a good sense of grip and a very good ear. These are the key differentiating factors of the talented drivers and form the basis of the skill set required to be able to ride the traction circle. Of course, this inherent skill becomes even more pronounced in wet conditions, which is why for me, a valuable stepping stone in the evolution of any race driver is to race on ice or dirt.

Stability index

The last thing that separates the mega stars like Fangio, Clarke, Senna, Schumacher and Hamilton from the other professional drivers is their ability to tolerate low values of stability index. It was often said one of the defining features of Ayrton Senna was his ability to drive completely on the limit all the time. What Senna was doing was all the things we just talked about in terms of riding that difference between maximum self-aligning torque and peak tyre grip, keeping the combined slip at its peak while, at the same time, being able to tolerate low values of stability index.

To illustrate this, let's review the race engineering equation that combines the lateral load transfer distribution at the front vs grip and stability index. This is shown in **Figures 4a** and **4b**.

Note how closely the stability index, being very close to zero, lies in terms of the peak of lateral grip. The ability to be able to both tolerate that condition, and exploit it, is what separates the champions from the bulk of the field.

In terms of quantifying this, and exposing the drivers with and without talent, here is where a well calibrated lap

The ability to operate within this zone of detecting when steering torque starts to get light and fuzzy is the first element that sorts the drivers with talent

You are never going to achieve perfect steer correlation, and to do so is actually counter productive

time simulation model becomes your best friend. I don't just say that because I have a vested interest, that comment comes from years of experience of having ChassisSim save mine and my customers' skins.

Firstly, the model knows exactly where the grip is. It's also consistent and has no concept of its own mortality. Consequently, it presents a very honest comparison. That last point about mortality, incidentally, can be tempered by ChassisSim's stability settings, but that is a discussion for another time.

Traps and pitfalls

All that being said, there are still some traps inexperienced players can fall into.

Firstly, you are never going to achieve perfect steer correlation, and to do so is actually counter productive. This was a huge lesson learnt in the ChassisSim Driver-in-the-Loop development. Let me illustrate via a war story. When I was testing with one of my GT3 customers, we had a terrible first day. So much so, I pulled the plug mid-afternoon and chased down the engineer on that car and we re-modelled it together. **Figure 5** was the end result, where coloured is actual, and simulated is black.

Note the close correlation with the steering that the car's engineer and I went to a lot of trouble to achieve.

The next day, we went back on the DIL rig with this updated model and the results where an eye opener. Firstly, it was a lot closer, but the model continually understeered. So, to tune it, we added five per cent front grip and took away five per cent rear grip. Ta da! The steering correlation was spot on.

This rams home a key point: even your best drivers aren't going to totally nail the grip thing, so keep that in mind. However, this also puts into sharp relief everything we have discussed about the knock-on effect of *over* relying on DIL simulators, and sacrificing track time.

That said, the difference between the simulated vs actual steering trace tells you an awful lot about the form your driver is in. Consider **Figure 6**, which is a correlation between an on-form V8 Supercar driver and ChassisSim. Again, actual is coloured and simulated is black.

Fig 5: End result of lap time simulation correlation with a customer GT3 car

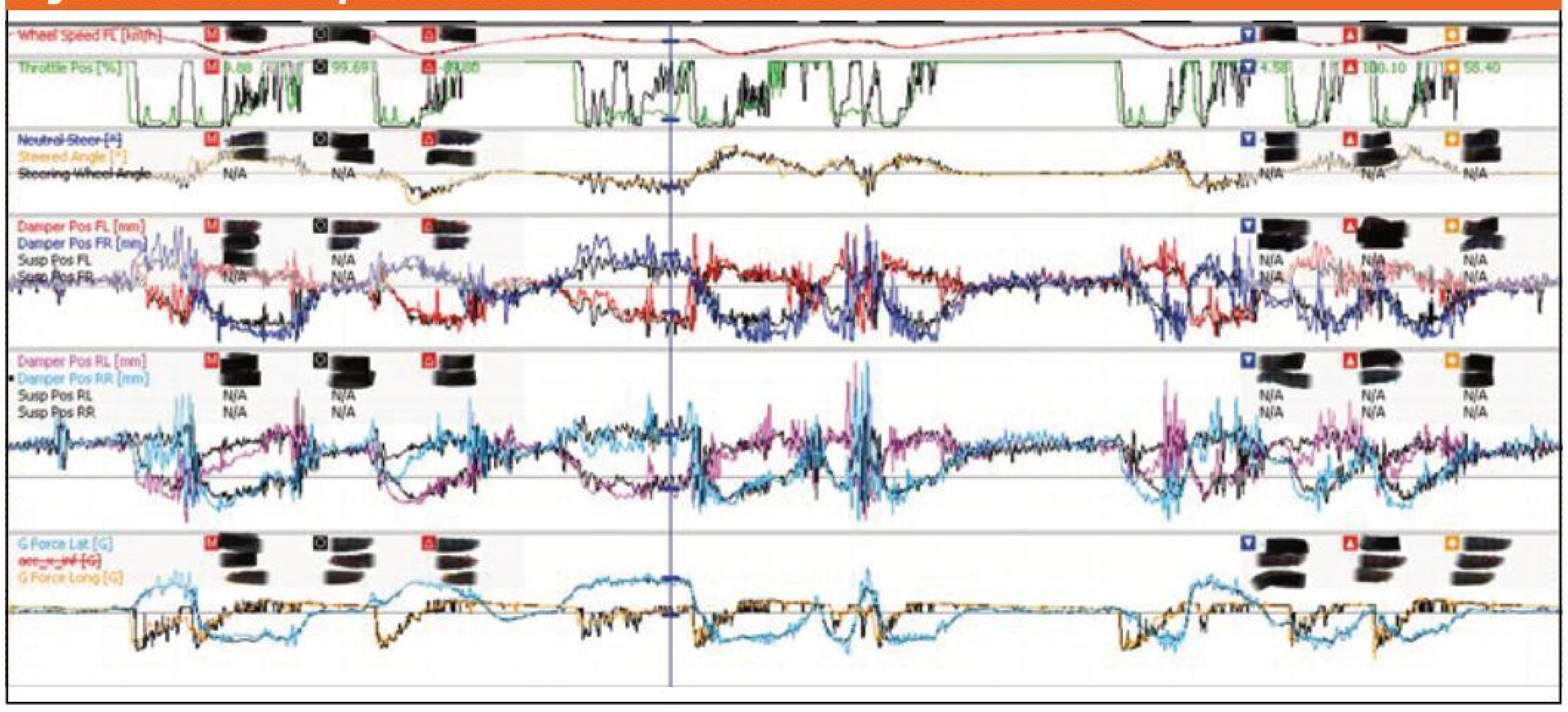
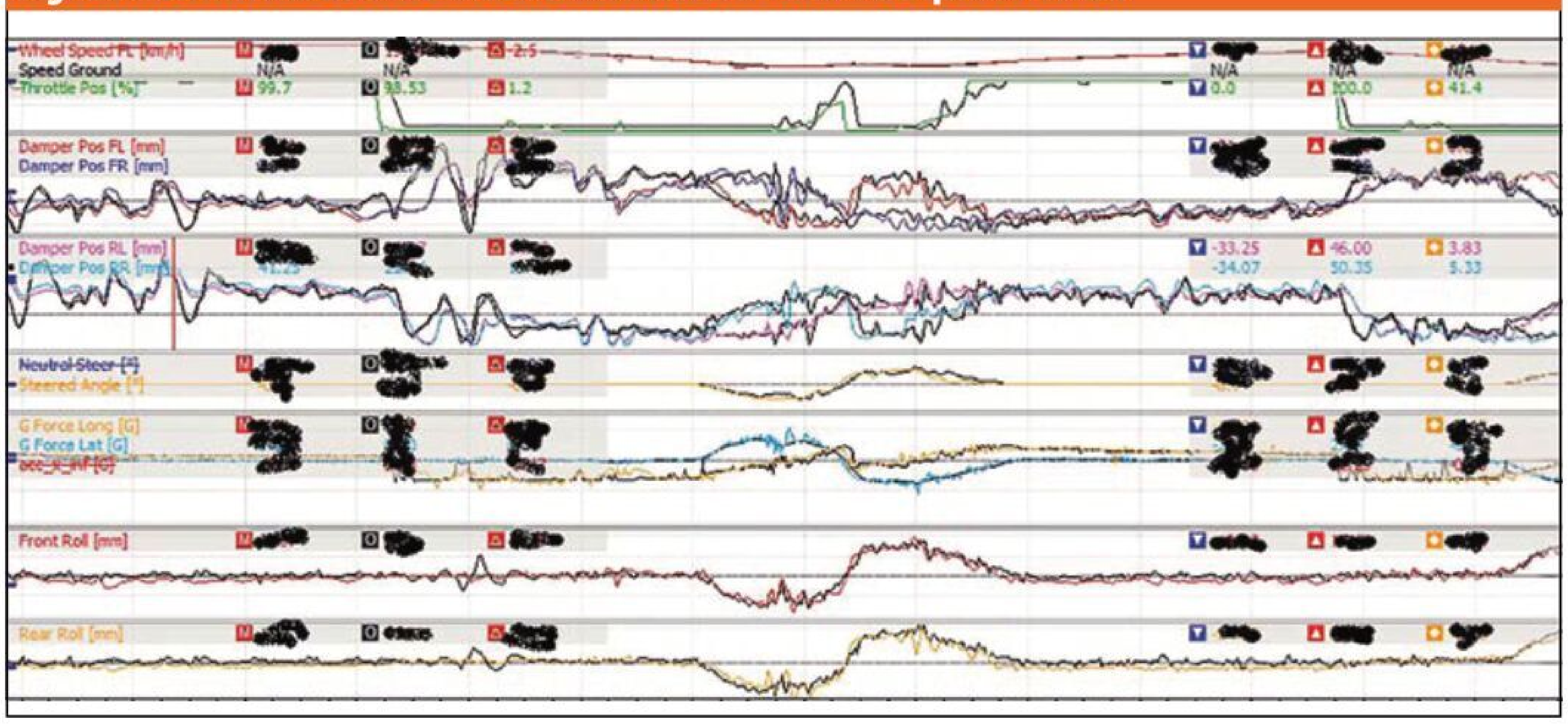


Fig 6: Correlation between ChassisSim and an on-form V8 Supercar driver



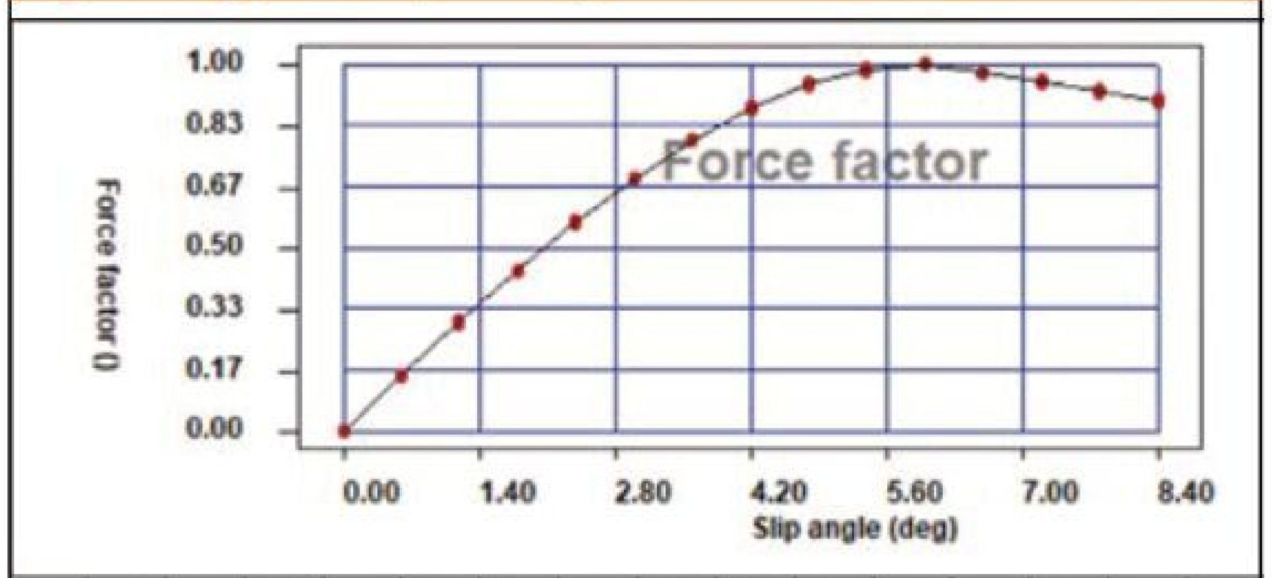
Note the similarities in steering application and longitudinal *g*. This is an example of a driver at their zenith. However, what tends to happen as the driver passes the zenith of their abilities is the steering lock they apply starts to increase and they begin to lose that ability to nail the lap time simulation under brakes. That all goes back to what we discussed in **Figures 1** and **2**. It takes a tremendous amount of ability and an innate sense of feel to drive on that limit, and only the very best can do that.

Quantifying the results

So finally, how do we quantify all this? Well, I can't speak for other simulation providers, but in ChassisSim this is where the tyre force modelling toolbox that reverse engineers tyres from race data comes into play. However, it comes with an important caveat that I've only caught onto over the last few years. As mentioned earlier, drivers invariably throw in too much steering lock, and this means you have to pay particular attention to the post-stall bit of the tyre curve. You want it looking something like **Figure 7**.

How this drops off will depend on your tyre, and this will require some tuning. Because the tyre force modelling toolbox is based on track replays, you will need something substantial to lean on when

Fig 7: Suggested post-slip curve



S angle	0.00	0.60	1.20	1.80	2.40	3.00	3.60	4.20	4.80	5.40	6.00	6.60	7.20	7.80	8.40
FFact	0.00	0.15	0.30	0.44	0.57	0.69	0.79	0.88	0.94	0.99	1.00	0.97	0.95	0.92	0.90

you exceed the post-stall region of the tyre, which is invariably what the driver will do. But do this correctly, along with all the other stuff I have discussed over the years, and the end results will take care of themselves.

In conclusion, there are a number of elements that make a really fast and repeatable racecar driver. The first is the ability to tell the difference between the peak of self-aligning torque and where maximum grip is. Second is the ability to keep the tyre at peak combined slip. Those drivers that can do that *and* tolerate and exploit a low racecar stability index are the real champions.

If you, the engineer, can correlate all that with lap time simulation, you will have a very good gauge of those drivers that have got it, and those that haven't.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Porsche on track for '23 debut

Porsche has continued to test its new LMDh Prototype that the German manufacturer will debut at the Daytona 24 Hours in 2023. However, delays to the hybrid system components, including the MGU-K and the battery, suggest the car has been testing without the full system.

The Porsche programme is run by Penske Motorsports, and the car completed more than 2000km at Barcelona in February.

'The focus of the test runs was to set up the systems, develop the tyres and optimise the interaction between the V8 turbo engine and the hybrid elements as described by the regulations,' read the press release from Porsche.

'The successful tests in Barcelona were an enormously important step,' said Thomas Laudenbach, vice president of Porsche Motorsport. 'During the first laps on our test track in Weissach it was critical to ensure that the basic functions of the LMDh prototype worked. In Spain, we saw the entire scope of development: endurance runs, set-up work and, very importantly, the optimisation of the interaction between all the partners involved in this project.'

The car is the first LMDh to hit the track, with the chassis supplied by Multimatic, which will supply all the VW Group manufacturers competing. The company confirmed it has delivered its first chassis to Audi ahead of testing later this year.

Hoch Zwei

Porsche LMDh has seen extensive track testing already, but early testing has been without the full spec hybrid system in place

High-Tech lights for UK circuits

Motorsport UK, the British Motor Sports Training Trust, and the UK's largest race circuit owners have announced that there will be a roll out of FIA High-Tech light panels across the top Motorsport UK-licensed race circuits, starting this spring.

The group will work with EM Motorsport, a principal supplier of electronic safety devices, sensors and custom-built systems to the motor racing industry. The move comes after Motorsport UK conducted wide-ranging discussions into the safety of marshal posts.

All UK circuits that have FIA International Grade 3 and above status will have the light panels fitted.

'Providing a safe environment for our sport to thrive is at the heart of Motorsport UK,' says Hugh Chambers, CEO of Motorsport UK. 'It is essential we provide safety for competitors and volunteers alike who deliver the sport every weekend throughout the UK. The roll out of the FIA High-Tech panels represents a significant step forward in modernising UK race circuits by adopting the latest and most advanced technology.'

Wild horse wild card

Ford's Mustang is by no means an exclusive car, yet the manufacturer has had the concept accepted for competition in the US by IMSA

Ford has confirmed it will build a GT3 version of its Mustang for the 2024 IMSA WeatherTech series, but the car has yet to be homologated for competition anywhere in the world, and has already proven controversial among the European teams and series.

The Mustang will feature a 5.0-litre Coyote V8 taken from the manufacturer's road car range. The engine will be developed by M-Sport in the UK, the rally specialists which also developed and ran the Bentley Continental GT car in the Blancpain Endurance Series. The new Mustang will be built by Multimatic, but currently does not meet the minimum price point set for GT3 cars.

The FIA's own requirements are that the entry-level production car has a minimum price of €70,000, set to include cars such as the Ferrari 488, Mercedes SLS and Porsche 911, but exclude those not considered exclusive. That leaves the FIA in the uncomfortable position of having to either ignore its own homologation requirements, or watch as IMSA welcomes a GT3 special into its series.

The Mustang will have to undergo some revisions compared to the road car, including the adoption of a rear-mounted transaxle to improve weight distribution and modified front and rear suspensions.

'If you read the rulebooks now, you're allowed to do considerably more than stiffer springs and fatter tyres to make the car faster,' says Larry Holt, executive VP of Multimatic Special Vehicle Operations. 'Pretty much in front of the firewall and in the back is all open. There are freedoms that the rules give us and it would be wrong for us not to take them all to the limit.'

The car will be built under new GT3 regulations that allow far more freedom than the original GT3 rules, which has allowed Ford to consider upgrading the Mustang. Previously it tried to homologate the Ford GT as a GT3 car, but that was rejected by the FIA.

Supporters of the Mustang say the prospect of Ford returning to factory motorsport against the likes of Corvette, Ferrari and Porsche is good for the category.

All change at Formula 1 race control

The FIA has confirmed it will change the way race direction at Formula 1 grands prix operates this year. It will introduce a Virtual Race Control Room, and a new directive that radio communications between teams and the race director will be removed 'in order to protect the race director from any pressure and allow him to take decisions peacefully,' says the FIA, which has also re-organised assistance to the race director.

The Virtual Control Room will be remote and will work similarly to VAR now used in football, and assistant referee in rugby. Teams will still be able to message the race director as they do in the WEC, but it will likely be a monitored digital system that replaces the radio communications that were broadcast on the television.

Similarly under review is the procedure to unlap cars behind the safety car, in a bid to avoid the chaos and backlash following the final round of the 2021 Formula 1 season.

Also confirmed was a change to the management structure in race control, with Michael Masi being replaced by FIA WEC race director, Eduardo Freitas, and Niels Wittich, supported by Herbie Blash as a permanent senior advisor.

'With this plan, FIA opens the way for a new step forward in Formula 1 refereeing,' said president, Mohammed ben Sulayem. 'Without the referees, there is no sport. Respect and support of the referees is in the essence of the FIA. That is why these structural changes are crucial in a context of strong development and the legitimate expectations of drivers, teams, manufacturers, organisers and, of course, the fans.'

IN BRIEF

Formula 1 has confirmed it is extending until 2025 its funding commitment to the **Formula 1 Engineering Scholarship** programme for under-represented groups, continuing its drive to increase diversity within the sport. The scholarships were launched in 2021, and will now be extended to support 10 students a year from 2022 to 2025.

The **Australian Supercars Championship** has confirmed that its new Generation 3 cars will retain H-pattern gear shifting when the cars are introduced into competition in 2023. The cars currently use **Xtrac's** P1293 six-speed gearbox. The 'box, dampers and rear suspension will be carried over into the Gen3 cars.

Extreme E, the off-road electric motorsport series, has revealed plans to launch an offshoot hydrogen series, named **Extreme H**. The new series is targeted for introduction in 2024 and will retain the same powertrain and chassis used in Extreme E. The key difference will be a hydrogen fuel cell will replace the battery as the principal energy source.

Hydrogen-fuelled series in line for 2024

Goodyear has been chosen as the official tyre partner for the **ERA Championship**, the new electric single-seat racing series that will launch this summer in support of the ETCR.

Charles Pic, the former grand prix driver for Marussia and Caterham, has agreed a deal with DAMS team principals, Olivier and Gregory Driot, to take over the team founded by their father, Jean-Paul Driot. The driver line up and team personnel will remain unchanged for 2022 as the team campaigns the FIA Formula 2 Championship.

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Fallibility report

Mistakes happen, and they're an integral part of the joy of motorsport

As a self-confessed Luddite, I am happy to admit I have never before downloaded or listened to a podcast. However, having driven from the south of England to Scotland overnight for the school holiday mid-February, I broke the habit and downloaded the Reith Lectures that were broadcast on Radio 4 and are available on the BBC Sounds app, which I also downloaded for the first time in order to do so.

The topic of the 2021 lectures was living with artificial intelligence (AI) and the series covered how AI already affects major areas of our life, including warfare, jobs and the economy. It was a fascinating series, dealing with the effects that have already been felt, regulating what is being studied now (particularly in the area of warfare), and the future. The series got me thinking about how AI is increasingly being used in motor racing. Lawrence Butcher covered the topic within the pages of our previous edition but there is a direct conflict, I think, between the use of AI in competition, and racing itself.

As we discussed in the March edition, AI use in racing is in its infancy and there is still a long way to go before it can be used reliably, and efficiently, but teams are starting to grasp the basics of its application in terms of strategy and design and put it to good use.

There is direct conflict, I think, between the use of AI in competition, and racing itself

Life is…

While some fear the rise of robot intelligence, and consider the human race doomed as a result, the Reith Lectures seemed to settle on the point raised by Tommy Lehrer many years ago that life is like a sewer: what you get out of it depends on what you put into it. Computers are the same. They are able to efficiently repeat a task multiple times, and will churn out a result, but they only react to human input. If that's wrong at the start, the result will be wrong, and probably multiplied many times over.

Computers cannot be relied upon to come up with a solution all on their own. One such example given in the lectures was a house robot in charge of feeding the children, which might consider the fridge to be empty and start to calculate the nutritional value of the family cat. Humans still need to have control over the result, meaning computers will never be able to dictate an outcome.

Increasingly, race teams are using AI to make multiple calculations at a speed beyond human capability, and make connections between various calculations that may elude the average human brain. Or simply take too long. A computer will take the human input and spit out an answer, which for a team that has invested should give an advantage over one that hasn't. The issue will come when everyone has it, and then it becomes a matter of who has the *best* system. At that point, the battle of the brains will change from engineers to software programmers.

Missed shift

The conflict between this and racing is that the sport itself relies on fallibility. No one wants to know the result of a race before it starts, and the best races are usually those with a variable thrown in, such as the arrival of rain, for example.

A missed gearchange was always a favourite before semi-automatic gearshifters became *de rigeur*. Mechanical reliability is now vastly improved to how it was in the 1980s, and so in a more traditional race we instead rely on the driver, or team, to make a mistake to maintain interest for the viewer. Easier to do that in endurance racing than sprint, I would argue, but it's not exclusive.

However, when there is a fallible element to the sport, suddenly the world erupts with an extraordinary amount of hand wringing. I am referring, of course, to the winter of discontent following the final round of the Formula 1 World Championship, and the decision of the race director that undoubtedly influenced the outcome of the drivers' title.

Indeed, the internet erupted with such voracity that it cost the race director his job. Maybe he deserved to lose it, maybe not, but it was clear mistakes will not be tolerated by the fans, with some even going so far as to demand the result be reversed. This is pure lunacy of course. Let's go back over all sporting injustices and right them, shall we? Or maybe we just have to accept humans *do* make mistakes.

With F1, NASCAR and the WRC entering new eras this year, and with IndyCar, IMSA and Australian Touring Cars also developing new cars, I could imagine AI support would help make decisions by the regulators.

However, in everyday races, AI has the potential to further remove fallibility from normal race situations. Soon we may be relying only on the driver to make the mistake and, if they do that too often, they too will get crucified. One hope is that AI will churn out all answers, including risky set ups that may lead to destruction, and teams still have the human input to implement these if they are quicker, and take the risk. Just ask Pirelli. There's hope yet.

ANDREW COTTON Editor