Running a Racecar

Modern racing technology – the inside story

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From the experts at Racecar engineering

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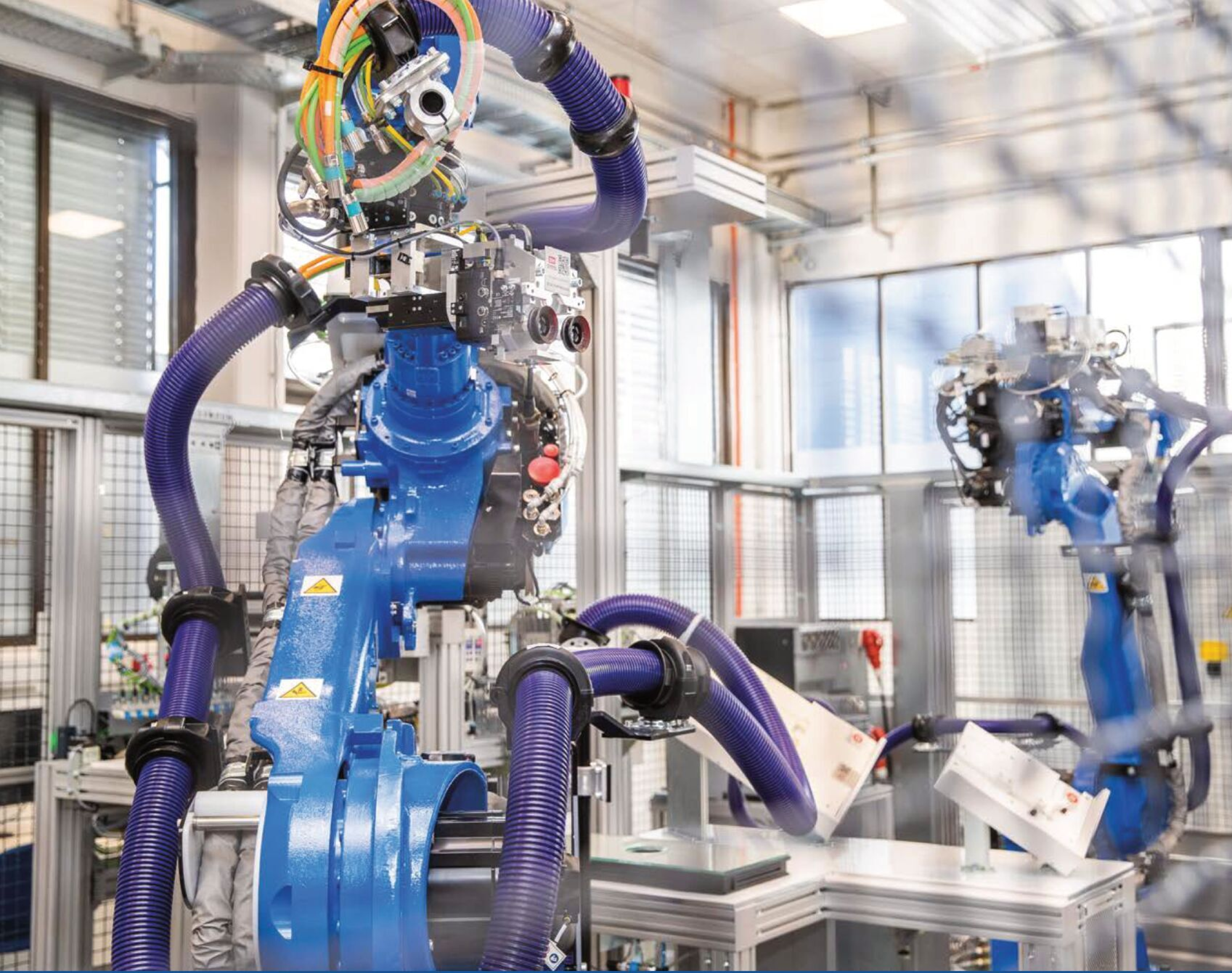

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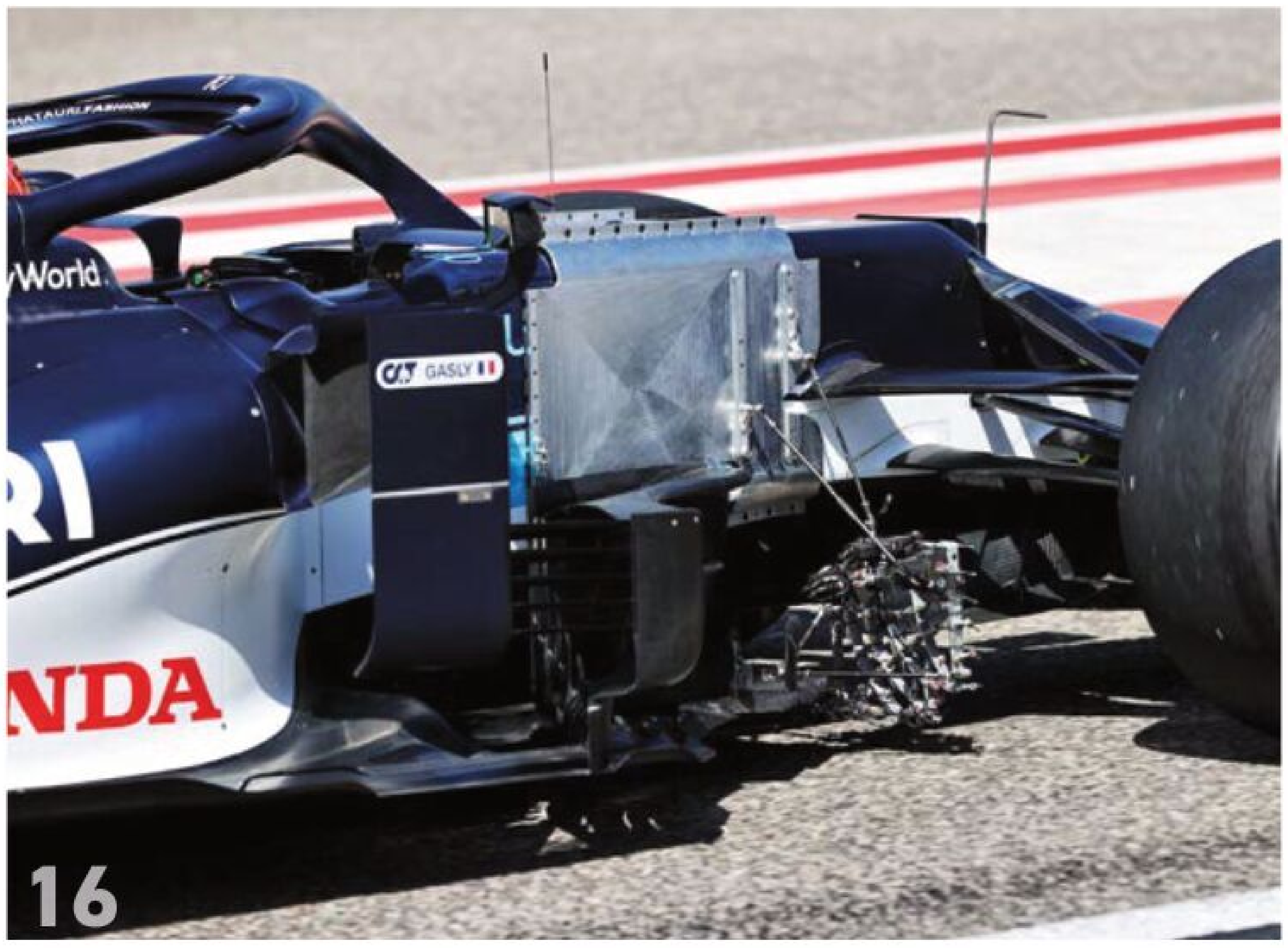
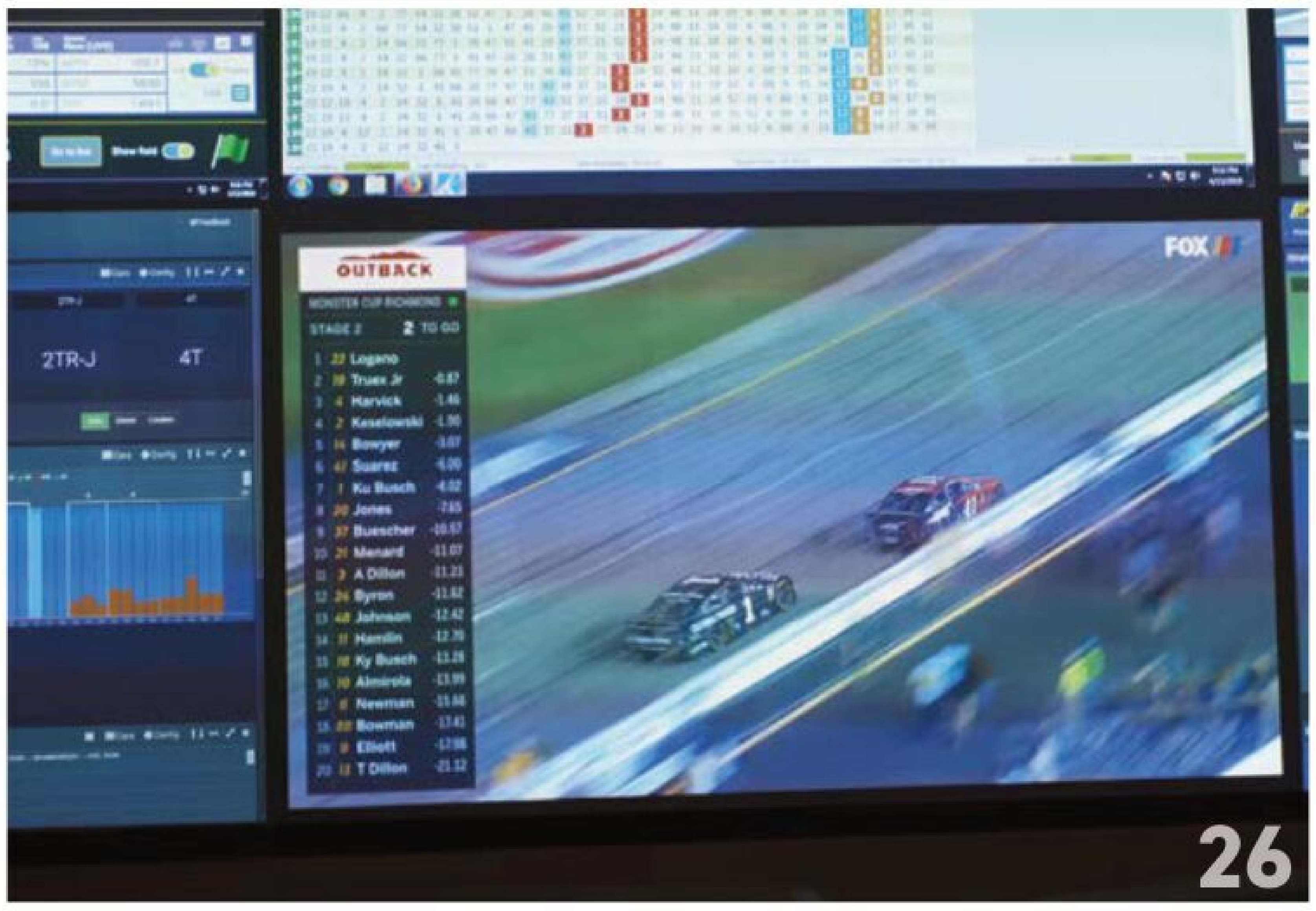




Strategic planning

A good race engineer will have a plan until the race, when you have to change it

By Leena Gade

In the days of social distancing, I found myself devising a strategy to get myself and my mother safely through our daily 45-minute walks through suburban London with minimal human contact.

Pre-pandemic, walking around London was already a little tricky. Seeing a Londoner approach can induce mild panic. Should I keep to my trajectory and hope they move, or will we have an awkward, side-stepping stand off? Should I say 'Good morning' or will they think I am crazy?

To avoid as much of this as possible, I worked out that early morning walks are best as there are fewer people around but, for many reasons, we never made it. So we went for the next best thing, early evening walks.

On our first outing a jogger came up behind us on a pavement two people wide, with a three metre grass verge alongside. Now, I sometimes jog, and I'm acutely aware that when you come running up behind someone you can startle them, so I generally make some sort of noise to warn them I'm coming past. I then take the grass verge route so I'm the regulation two metres away from them and that seems to work.

Unfortunately, said jogger clearly had no strategy. She made a late, split-second decision and tried to pass right next to my mum, who I then pulled suddenly out of harm's way. That spooked the jogger and she swore at us as she went past. My typically polite mum then apologised to the jogger, and a little while later told me off for berating the jogger's obvious incompetence!

This situation need not have arisen if the jogger had planned and executed a better strategy. Which brings me to the topic of race strategy.

Crystal ball

When it comes to racing, there are a few factors that usually dictate how decisions are made. Most of the time, they are based on the information you have to hand at that moment, because trying to guess the future is not a reliable method. I know. I have tried.

Some years back, I was part of a team competing at the Spa 24-hour race. On the Sunday morning, it became clear heavy rain would arrive close to the end of the race. With a few hours in hand, there was plenty of time for people to overcomplicate the options. Thunderstorms are incredibly hard to predict and so, with such an unknown entity, you almost have to deal with it when it arrives. At least, after doing the obvious and having wets ready to go. Then, once there is an indication of intensity and when it will arrive, either commit to pitting and bolting them on or stay out and ride the wave.

Either way, at some point in the process the racecar will be on the wrong tyre for the conditions but, by communicating to the driver that things may get a little slippery, you have at least a fighting chance of being prepared.

Of course, much of the decision comes from knowledge of how the different tyres work in the rain, and also knowing whether the driver can under drive a car enough to still be fast out on track on the wrong tyres. This knowledge was available in this instance. What wasn't known was what decision the race director would take when torrential rain hit 30 minutes before race end, initially only on the run up to the Bus Stop but soon after across the whole track. A window of opportunity was available to pit and switch to wets, just as things were getting tricky.

However, with so much time before the rain arrived to think about scenarios, a team member believed there was a chance the race would be red flagged and that would be the end of the race. That's happened before.

After a number of cars had aquaplaned off, some shunting and sustaining damage, the race director called a full course yellow (FCY), not a red flag.

Michael L Levitt

Mazda won the 2021 Petit Le Mans under Gade's well-prepared, versatile race strategy

That put the car down to P5 from P2 within 20 minutes, only gaining one place back from an infringement by another car.

Maybe the outcome would have been the same had there been simpler thinking, but it was clear afterwards that basing strategy on second guessing someone else's decision is not normally successful.

Having race engineered a few races with pivotal moments that defined the strategy, I know such decisions aren't easy to make. And even when you're basing decisions on what appears to be reliable information, you have to be aware that in this business there can be fake news, too.

Importantly though, as the angry jogger proved, trying to make strategic decisions on the fly is never a good idea.

The knowledge

Going into a race having done all your preparation work is key to making the right decision at that critical moment. When you have the knowledge and compare it to where you are in reality, the strategic decision becomes simpler. And with less overthinking, there is less chance of error.

Consequently, I think I always make decisions in my daily life with strategy in mind. I can't help it. I always choose a seat in the forward part of a 'plane so, when I get off, I reduce the need to overtake other passengers. Should there be a staircase to connect the gate to a walkway, I'll take that and scoot past the crowds on the escalator. In my head, it's all about the path of least resistance that means the journey will be faster from a to b.

Returning to our London jogger, how much planning did she really need to execute the overtake safely and with minimal fuss? She had all the knowledge at her disposal. She could see us from quite far away and our trajectory was clear. She knew she had to pass with a two-metre gap. She knew there was sufficient space beside us on the grass. She knew her approach speed and our walking speed, and could roughly estimate our convergence. She could see the path in front was clear. She also knew we were very unlikely to know she was there.

» Trying to guess the future is not a reliable method

Even allowing for processing all that information, I reckon it would take about five seconds to make a qualified decision and, if done early enough, allow for a double check just before the decision to commit a line was needed. But she didn't do any of that. Instead she got me into trouble with my mum. Unforgivable. ●

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

Kyle Wilson-Clarke celebrates victory after a successful Le Mans with his drivers in 2013

The conductor

Understanding the critical, multi-faceted role of a race engineer

By Jahee Campbell-Brennan

» **The race engineer is a people manager. Having good communication skills and being a good delegator is essential, as is being methodical in approach and having good project management skills'**

Gerry Hughes, motorsport and high-performance vehicle engineering consultant

It's a tough job, but somebody has to do it. The over used phrase applies to many roles within motorsport, but perhaps none more so than to the race engineer. Any race team, at any level of the sport, comprises numerous moving parts, some human, some otherwise, and each have their own part to play, but the race engineer is arguably the most critical of all.

As the first point of contact between the driver and the car, and then between the car and the rest of the team, the role is widely varied in responsibility, and constantly evolving as technology and vehicle systems move relentlessly forward.

To the driver, the race engineer has responsibility for providing a car that is both driveable, and performs to the limit of its capability – a job that involves interpretation of a wide range of inputs, from verbal feedback from the driver to sensor data from the chassis.

To the wider team of mechanics and other technicians, the race engineer is responsible for, at the most basic level, defining fuel loads and tyre choices, but they are also required to take ownership and coordinate the rest of the team to ensure the racecar is mechanically sound and ready to perform at competitive pace.

Evolving occupation

A few decades ago, the race engineer's job was relatively simple – attend race and test events, oversee running the car and develop a platform to provide the driver with the best compromise of driveability, pace and tyre management. Today, that job has evolved into a very different, more complicated occupation.

At top-level motorsport, the race engineer's role has grown enough that they now have an entire team of engineers working alongside them to help manage their expanded list of responsibilities, and therefore a broader range of engineering expertise to draw upon.

Performance engineers, data engineers, controls engineers, tyre engineers and powertrain engineers are all essential personnel to accompany the race engineer trackside and help ensure the car is running reliably and to its full potential in the race.

The scope of the role remains largely the same, but the science has become so involved that some of the duties necessarily now must be delegated.

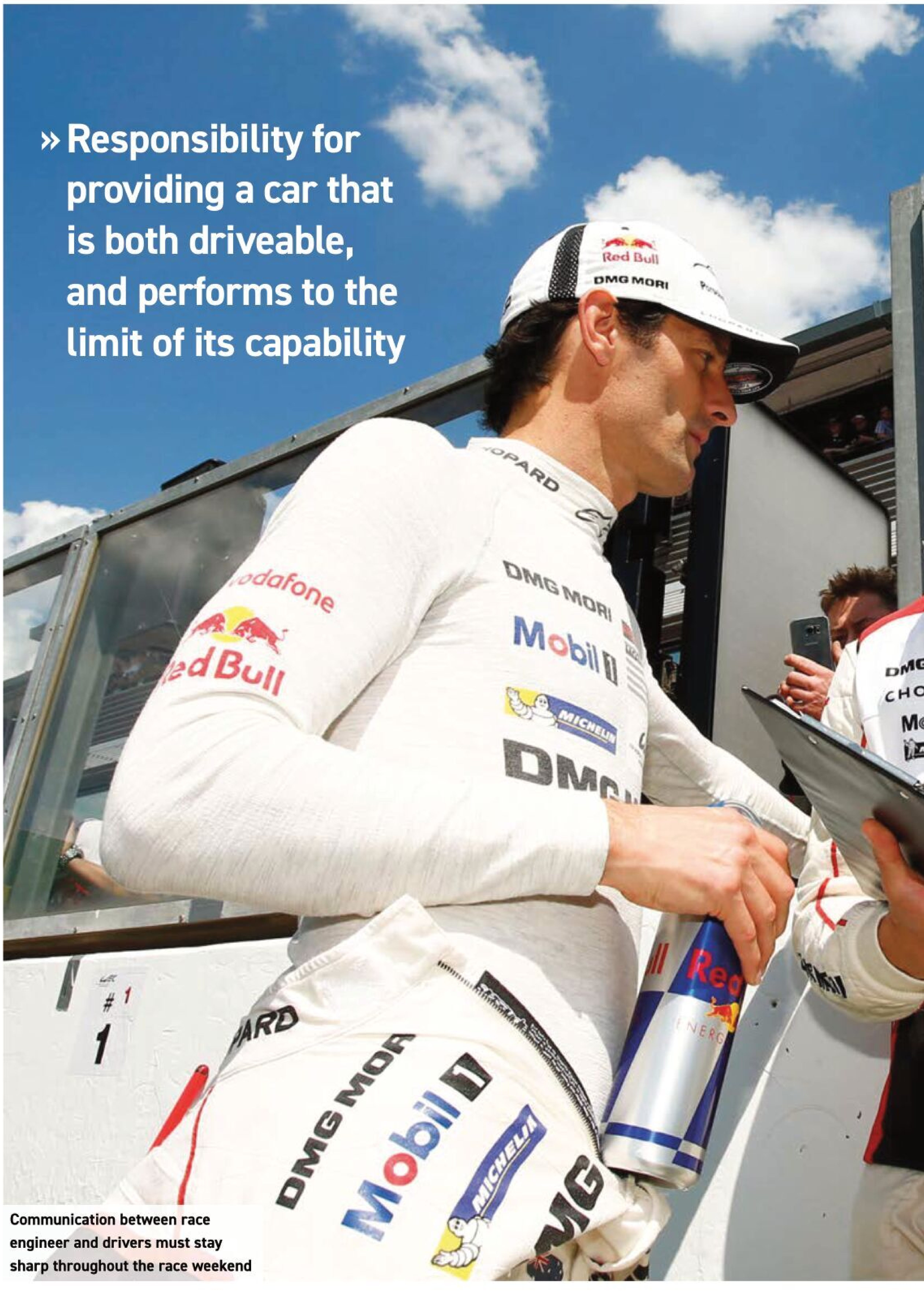
Taking the most fundamental point first, the responsibility for the performance of the car on a race weekend means arriving at the best compromise of chassis, aerodynamics and powertrain set-up. As such, successful race engineers have a deep understanding of the fundamentals of vehicle performance. That generally – though not always – involves being educated to degree level in mechanical engineering, or a similar subject(s), and then building on that with first-hand knowledge of the interactions between the various vehicle subsystems.

Modern racecars are particularly complicated machines, so part of the role involves bridging the gap between the technology and the driver – an interpreter, of sorts – for the various behaviours and characteristics of the two.

'The race engineer is a people manager. Having good communication skills and being a good delegator is essential, as is being methodical in approach and having good project management skills. Because, at

The race engineer must work very closely with the drivers to deliver a car they're happy with. Here, Gerry Hughes chats with David Coulthard in 2005

» Responsibility for providing a car that is both driveable, and performs to the limit of its capability



Communication between race engineer and drivers must stay sharp throughout the race weekend

» I do see myself as a bit of a cheer leader. Away from the technical side, it's also our job to motivate people and be sure they stay focused through the weekend

Kyle Wilson-Clarke, race engineer

the end of the day, you've got to be able to manage people ie the driver,' comments Gerry Hughes, motorsport and high-performance vehicle engineering consultant.

'You can sit by yourself driving things from first principles all day long but if you can't communicate that to mechanics, or others working around the car, and get them to understand what you're trying to achieve, it's a waste of time.'

This is particularly important with the current generation of hybrid powertrains, and the effect they have on vehicle dynamics. Few drivers have had the chance to gain high levels of experience with these racecars, and can have a difficult time appreciating the scientific principles behind a sensation they are feeling in the car, which makes explaining them, with the objective of improving certain driving characteristics, a little harder.

'To me, a big part of the role of a race engineer is marrying the technical aspects of the car into a language the driver can understand. Moving from 'technical' to 'driver' language. Being the one point of contact between the driver and the car, we have to extract what the driver needs in terms of getting the most out of the car from their feedback,' adds Kyle Wilson-Clarke, race engineer with experience in categories such as WEC, Le Mans 24h and Formula E.

Personnel manager

Dealing with thinking and feeling humans requires a very different skill set to interpreting science and engineering, so the race engineer must have a certain level of psychological appreciation, in addition to the ability to interpret the technical language.

Managing confidence and fatigue are very important considerations in a driver's ability to extract maximum performance from the car over race distance, especially in endurance racing. The technically fastest set-up on paper is rarely the easiest to drive quickly, consistently and for extended periods.

'I do see myself as a bit of a cheer leader. Away from the technical side, it's also our job to motivate people and be sure they stay focused through the weekend. It's a very diverse role,' adds Wilson-Clarke.

'If you want to be a race engineer, you can be the most technical person in the world but, if you can't interact with your drivers, it can make life quite hard.'

The bottom line is that engineers can't do what they do without drivers, and *vice versa*. It's a very symbiotic relationship.

Take it from a team principal: 'I've seen driver and engineer pairings that have worked supremely well, and others which haven't. It's often not a luxury we have but, if you're looking to extract the most performance from a pairing, you'd certainly want to match the personality types of your driver and race engineer,' notes Hughes.

A weekend's work

The race engineer's role is clearly broad, dynamic and high pressure, so let's walk through the practicalities of the job over a race weekend, starting with pre-race practice.

'At a race weekend, my jobs tend to start with planning practice sessions where I look after communication with the driver, ultimately making sure they fully understand what our approach to the weekend is,' explains Wilson-Clarke. 'An important tool to prepare in advance of the weekend's practice sessions is an itemised schedule for the day, the run plan, which it's my job to generate.'

James Urwin (left), Williams Racing race engineer, discusses performance data with driver, George Russell, at the 2021 Dutch GP practice day

Typical items featuring on a run plan would be directed at exposing the car and driver to certain scenarios in order to gather data and improve understanding of its characteristics. For example, performing a run through of a range of wing settings to gather an understanding of their influence on aerodynamic balance, or running a number of roll stiffness distributions to find a chassis balance that provides the best combination of driveability and tyre wear patterns.

'Taking an example of a 45-minute practice session, you'd have every lap itemised by objective. That means also understanding how long it takes to complete each lap, and how much time to budget for calling the car in for tyre change, or a set-up adjustment if you need to react to something. It's a way of planning and executing the session to tick off all your items efficiently and reliably,' continues Wilson-Clarke

These run items can be scheduled directly by the race engineers or be requested by the performance / simulation team specifically to verify and correlate data to the simulation models. Ultimately, though, the race engineer is responsible for completing the run plan.

'Formula E is very restricted in terms of practice running time, but this still comes into play. Things like qualifying simulations, energy laps, specific braking assessments etc. I have to make sure those are performed efficiently and that we set aside enough time for them over the weekend, so they'll all feature on the run plan,' says Wilson-Clarke.

Between practice sessions, the driver and team must also go through debriefing – another job led by the race engineer.

Debrief meetings are an opportunity for the team to come together and go through issues which arise during the outings. The driver will discuss any changes to the car they would like in aid of driveability and the race engineer will discuss these with the performance engineer who may also suggest adjustments to be made after reviewing data.

The run chart

As the weekend progresses and race start approaches, the race engineer also has to coordinate the team of mechanics to ensure they are fully aware of the plan for race day, and what may be required from them.

There is generally very little time between outings during practice sessions, so the whole crew of mechanics needs to be orchestrated and engaged with what is expected when the car comes in for a stop. This covers not just tyres and fuel, but set-up changes and other mechanical adjustments.

Traceability and organisation must be very tight in order to run a car successfully, so the race engineer must have a framework in place for documenting and communicating the runs and any issues that arise.

During each outing, certain information will be recorded on a document, sometimes referred to as a run chart. This is a way of formalising observations made during a run.

Live data such as lap time, fuel consumption, safety car events and other important vehicle information is noted in this document for future reference and for communication with the wider team.

'This allows you to make notes of live feedback. For example, we might make a ride height change, the expected result of which was x, but from the data we got y and the driver comment was z,' clarifies Wilson-Clarke. 'We can then ask ourselves if this aligns with our expectations, or doesn't, and be sure we have a process in place to investigate and feed this back to the rest of the team.

'This also allows space for driver and engineering comments.'

For many championships, race set-up will be different from qualifying set-up, and the pace in each can differ in lap time by several seconds. This is motivated primarily by the realities of tyre management. Qualifying generally requires absolute maximum pace, but only for one lap, which is a very different concept to managing whole stints.

Qualifying set-ups tend to be very aggressive, putting a lot of energy into the tyres to bring them into their temperature window as quickly as possible, which also means they don't stay there long and can quickly overheat and wear very fast.

For a race set-up, particularly in endurance racing, this aggressiveness must be dialled back to prolong tyre life and wear rates at each axle. Practice sessions are about finding the optimal compromise between the two, with the race engineer's direction, to ensure the set-up is not only fast, but also that the driver is happy and comfortable driving like that for prolonged periods.

» If the driver has confidence in the race engineer's decisions on set-up, they will have the confidence to go out and drive to win

Gerry Hughes, race engineer

'A lot of the overall performance of a package from the top down is related to the confidence of the driver. If the driver has confidence in the race engineer's decisions on set-up, they will have the confidence to go out and drive to win,' adds Hughes.

Plan of action

So, with the practice sessions dedicated to finding optimal set-ups for both qualifying and racing, the race engineer's focus shifts as preparation for the race session begins.

Before race start, the race strategy must be coordinated so, working alongside the team's strategists, a plan of action for the race is formulated; another job for the race engineer.

In the case of Formula E, where energy management is everything, this could involve deciding where and how to use the energy allowance. Does the driver push from the beginning of the race to get to the front of the pack and then conserve energy in the later stages? Or hang back in the middle of the pack and push hard in the closing laps? These calls can win or lose a race.

For the race engineer, the duration of the actual race is a process of working with the wider team to monitor the car's health and performance via telemetry (if rules permit), ensuring the mechanics are alert for pit stops

and prepared with the right tyres and fuel loads, as well as coaching the driver through the event via radio communication.

The human factor of driving must be emphasised again here. Some drivers like to be talked to and kept aware of competitor positions and incidents as the race progresses and fatigue sets in, others might just want to hear a familiar voice and some encouragement to keep the energy high.

This is where the relationship between driver and engineer can become very personal, perhaps even extending beyond strictly professional. When communication is strong, and the bond is strong, the two form a very powerful duo.

With the added mechanical and electrical complexity that the likes of modern F1, LMP1 and Formula E cars bring, communication between the two has developed an even heavier emphasis. With so much on-the-fly adjustability in the racecar, the driver must be instructed on how to manipulate certain functions for the particular racing circumstances they find themselves in.

'When I was with Porsche on the LMP1 programme, I was speaking to the driver three or four times a lap to advise him about traffic ahead and when to adjust the hybrid boost strategy to manage the regen' and deployment modes of the electrical system,' recalls Wilson-Clarke. 'Every single lap, for the entire 24 hours, I was communicating multiple times to advise on what changes to make. It was tough, but it kept me sharp!'

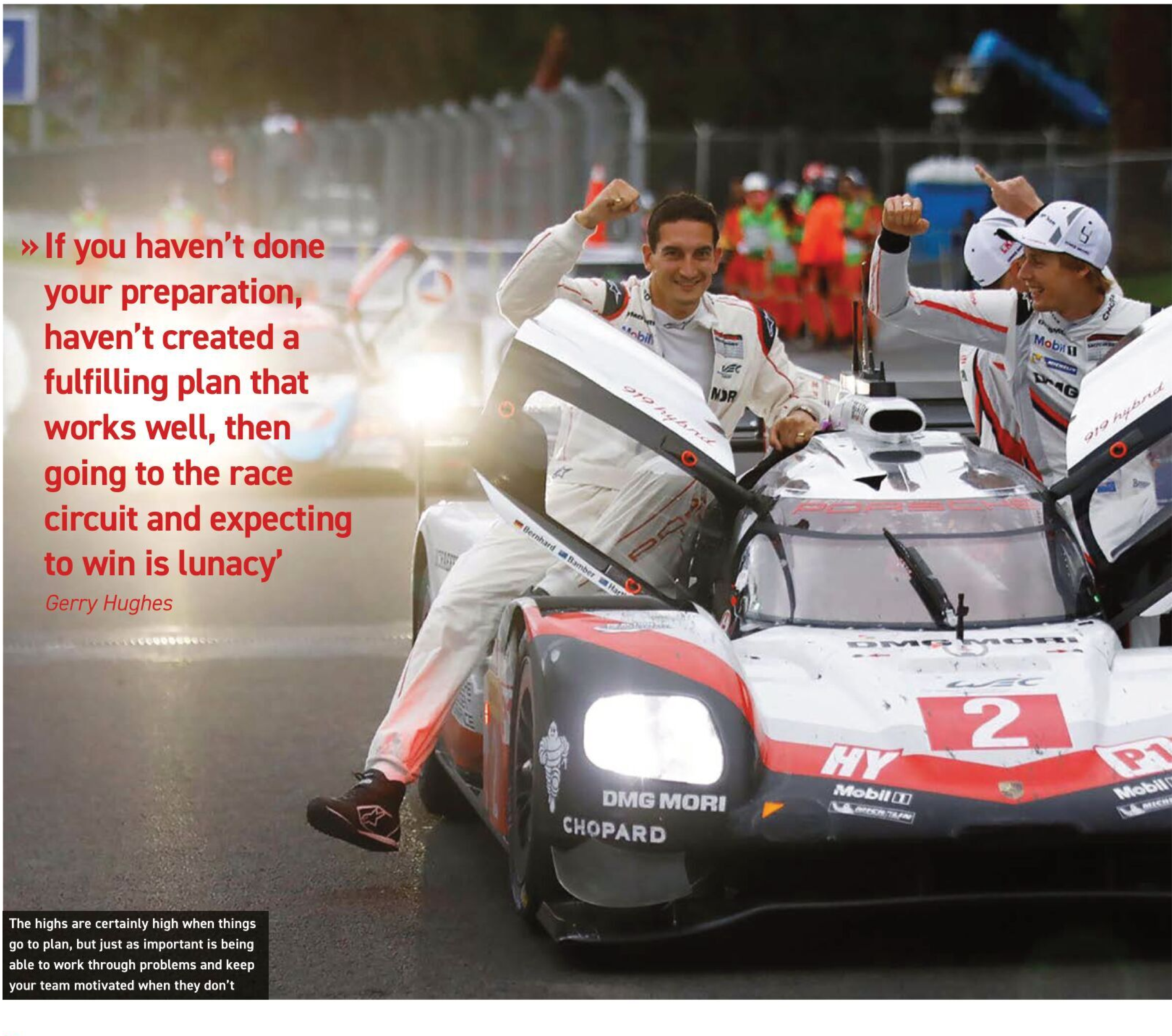
Decision maker

Under the pressure of a race, sometimes decisions must be made that take input from a wide range of variables, and the answer isn't always immediately clear, but the clock is ticking relentlessly. The right or wrong decision here can be the difference between winning and losing a race.

» As a race engineer, I never have to be the smartest in the room. That doesn't need to be my job

Kyle Wilson-Clarke

'There's nothing worse than being indecisive in key moments. Ultimately, you are a key decision maker within the team and you have to make those decisions as best you can, rightly or wrongly, to ensure the programme continues and the objective is achieved,' adds Hughes. 'Making decisions you're not confident with is seen very easily and, as race engineer, if you don't have confidence in your work then the driver and wider team won't either.'



» If you haven't done your preparation, haven't created a fulfilling plan that works well, then going to the race circuit and expecting to win is lunacy'

Gerry Hughes

The highs are certainly high when things go to plan, but just as important is being able to work through problems and keep your team motivated when they don't

A strong bond and a trust between engineer and driver adds to the effectiveness of the pairing

There will be times where a decision is made that isn't for the betterment of the race engineer, or their driver, but which put the team in a stronger position. Being a team player isn't to be downplayed in this role.

If all goes to plan, the race is executed flawlessly and the race engineer and their driver finish first, but that's still not the end of the weekend, or the race engineer's responsibilities. Before the celebrations begin, the team must again be debriefed.

Closing the loop

Post-race debriefing at the circuit is about reviewing the events and data from the car's logging system, as well as closing the loop of feedback with drivers, while the race is still fresh in their mind. The objective is to understand what was done right and, just as importantly, what was done wrong. No matter how good a team is, there are *always* improvements to be made to edge the competition, so the focus at post-race debriefing is about continually learning and improving things for the future.

This all sounds like an engaging, challenging, yet very rewarding job, but of course it's not all roses. In any occupation, how you deal with the lows is just as defining in your success. Putting hard work in towards solving a particular problem and not getting the results you expect is tough, especially when it's not clear why. Much of engineering is ultimately problem solving, and that rings particularly true here.

Preparation is the strongest tool to utilise in the build up to a race weekend, and a huge amount of work goes into this behind the scenes, way before race engineers, team and driver arrive at the circuit.

'Track time is so precious these days as, ultimately, the opportunities to perform physical testing and practice have been reduced [across the board]. The number of tyres you get is also limited over a weekend so, if you haven't done your preparation, haven't created a fulfilling plan that works well, then going to the race circuit and expecting to win is lunacy,' concludes Hughes.

Digital revolution

With the power of modern computing, teams are increasingly turning to driver-in-loop (DiL) simulations to replace physical testing. To a race engineer, running a session on the simulator is no different to running a session on the track. Test plans must still be designed and executed, data analysed and new ideas for development explored, just a lot faster, and without the weather to contend with.

As digital technology grows in its application, a solid understanding of software and some basic coding skills are certainly advantageous. While the role rarely involves direct software development, understanding the capabilities and limitations of those who do will add to the race engineer's strengths.

'As a race engineer, I never have to be the smartest in the room. That doesn't need to be my job. I need to be able to go and speak to the real specialists who know their subject by heart, but might have no idea about what the engineer next to them is doing. I need to be able to marry the two together and bridge the worlds,' notes Wilson-Clarke.

'Experience is a really big part of it, which of course you can only get with time. But being open and receptive to additional input from other departments, not being too fixed and being able to adapt and react to all situations is really important. You can't just expect to rock up, run the car and make some changes. You need to do your homework and make sure everything is covered and thought about up front.'

Working within a team means being able to lean on the experience of those around you and motivating others when morale dips.

'When you think you're doing the right thing, but the results aren't coming, it makes you question *everything*, but you just have to keep going. Being determined, strong minded and positive is key,' says Wilson-Clarke.

So planning, preparation and organisation are just some of the ingredients to being a successful race engineer. It's a role that comes with a huge amount of responsibility and requires you to draw and gain inspiration from a wide range of departments, starting with engineering but ending with good old fashioned human communication.

Despite all the pressure, a race engineer remains a coveted position, with even a certain level of glamour associated with it. If you take a few of the ingredients outlined in this article and incorporate them into your approach, you'll be just fine. ●

Opportunity knocks

The digital environment may be evolving rapidly, but on-track test sessions are still the best learning opportunities

By Jahee Campbell-Brennan

With test sessions pared back to the minimum in many categories, they have become a more important tool than ever to validate all the simulation work in a real-world environment

» **Test sessions can be the first revolutions the axles have ever turned as part of a shakedown, or... focused on finding the extra tenth of performance from a set of tyres**

Opportunities to develop and evaluate components, to develop drivers and to sharpen the team are all integral parts of any serious motorsport development programme.

As the name suggests, test sessions are traditionally events in which the car, accompanied by the race team and development drivers, attend a particular circuit with the objective of putting laps under the wheels of their racing car for the purposes of exploration, investigation and preparation.

Test sessions can be the first revolutions the axles have ever turned as part of a shakedown, or much further into the development programme they can be highly specific, focused on finding the extra tenth of performance from a set of tyres.

Track testing is widely varied in purpose and execution, but can largely be divided into two distinct objectives: to evaluate reliability, or to develop performance.

With a brand new vehicle, the first scheduled tests are centred around reliability of the platform. After all the calculations are done in the design office, and parts are made, those valuable laps are the first real indication of whether the engineering is sound.

Q and A session

It's an opportunity to answer questions such as is the car running cool enough? Are the brakes getting enough air? Is the engine delivering enough power? Are suspension components withstanding the loads they're experiencing? And, perhaps most importantly of all, does the car last the race distance?

The format of reliability testing can vary largely depending on the application and the championship the car is running in. In the days when track test opportunities were more plentiful in F1, for example, and not limited by regulations, a reliability test could be a race distance of 200 miles. In testing for endurance races such as the Le Mans 24 hours, testing could cover a distance of over 4000 miles.

'When we were doing testing for the Porsche LMP1 programme, we'd do tests of up to 30 hours of non-stop running to ensure everything was reliable,' says Kyle Wilson-Clarke, race engineer with experience in top level motorsport such as WEC, Le Mans 24h and Formula E. 'We put a lot of work into serviceability and reliability. It was largely about making sure there was no degradation or failure in components over the course of a race.'

Whatever the application, once the team is confident the design, or specification, is robust and capable of withstanding race conditions, testing can shift to a more performance-orientated focus.

In contrast to reliability testing, performance testing is about developing the platform to extract the most performance in the context of tyre usage and chassis set-up, which includes vehicle dynamics, aerodynamics, if you're running in a hybrid or electric championship, energy management.

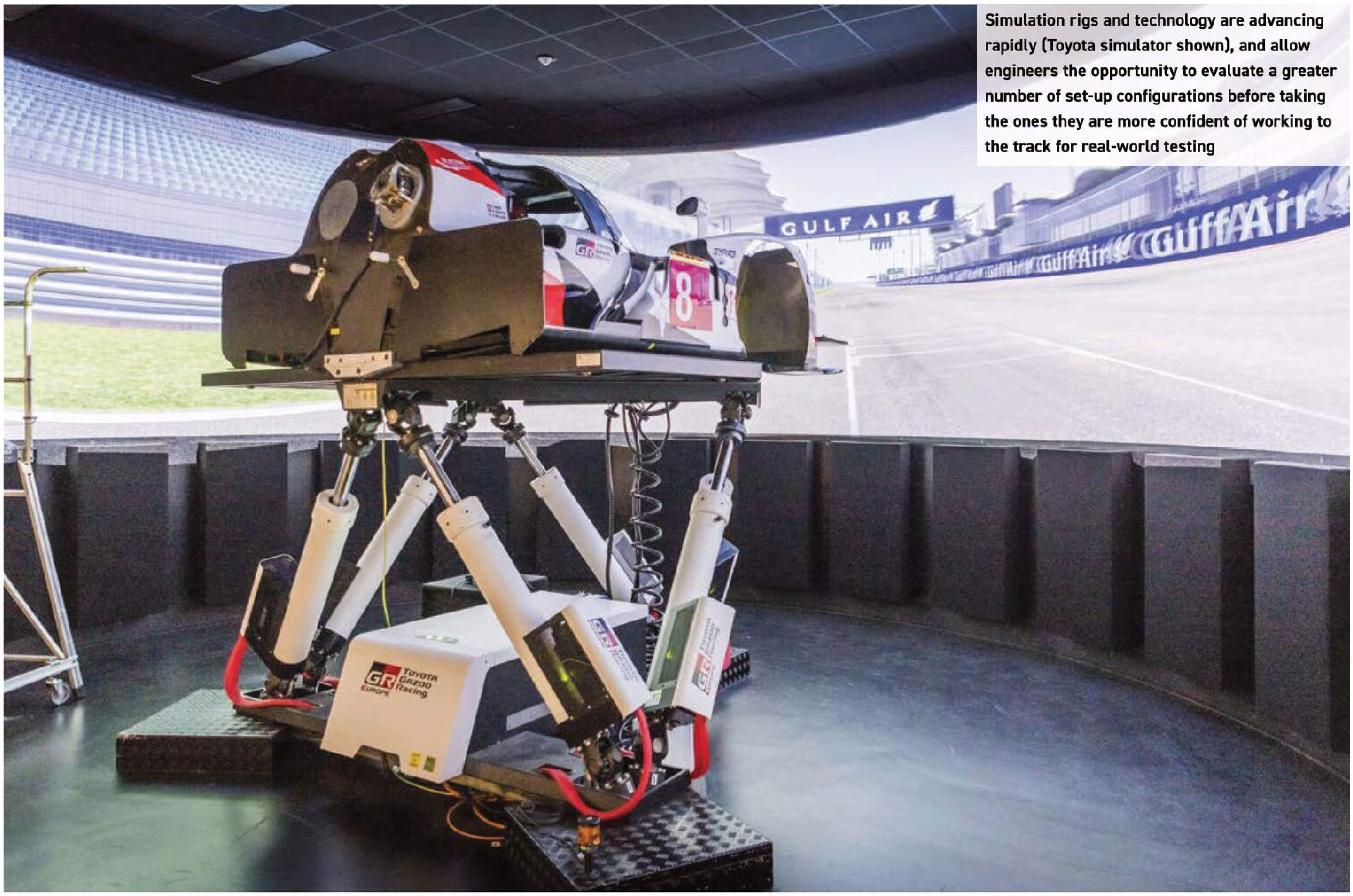
This form of testing can be performed in the lead up to a season or, regulations permitting, in between races as part of ongoing development.

In-season performance testing is very limited in most championships,

Good communication at test events is crucial as it enables drivers to understand what is expected from them during the run plan (race engineer, Kyle Wilson-Clarke, shown in the background)

» Track testing is varied in purpose and execution, but can largely be divided into two objectives: to evaluate reliability, or to develop performance

A new element that has become increasingly important in motorsport is understanding energy management in hybrid and electric racing series (Porsche Formula E car shown)



Simulation rigs and technology are advancing rapidly (Toyota simulator shown), and allow engineers the opportunity to evaluate a greater number of set-up configurations before taking the ones they are more confident of working to the track for real-world testing

so opportunities to test at the track are in short supply, which means they must be well prepared, well executed and profitable, in terms of learning.

'Ultimately, test sessions come down to having a defined set of engineering tasks or objectives you wish to achieve,' says Gerry Hughes, motorsport and high-performance vehicle engineering consultant. 'For example, you might want to evaluate a particular aero package for a track like Monza, or a super speedway, or you may have a high-downforce package you want to evaluate for a street circuit.

'Either way, you have a list of development items you want to evaluate and figure out what works well. This means understanding what the balance is like, what the driver likes, these kinds of things.'

Simulator sessions

Performance testing traditionally takes place on track, but more and more these days, especially in the higher budget championships, it is now performed using driver-in-loop (DiL) simulators.

Even though they're held behind closed doors, simulator sessions are essentially treated the same way as a real test session. The race engineer designs and executes the run plan, makes sure all items are covered and explores new ideas for development, in the same way they would at a physical test.

On top of being cheaper, and perhaps more accessible, than track testing, simulators allow a race engineer to scan more set-up configurations to narrow down on a performance window to investigate further with real-world testing.

In this sense, options the engineer can be confident are sub-optimal for performance can be discounted at the simulator stage rather than wasting valuable time at the track.

The philosophy of testing hasn't changed much over the years, but the emphasis and time spent on real track testing is a smaller part of the decision-making process now with the digital technology at teams' disposal.

The actual running of a test session is a process that starts back at base with the engineering director, who works with the team's engineers to define a high level test matrix that outlines the items they want to assess. The test matrix would then trickle down to the team's chief race engineer who decides who's doing what, how it will be tested and, if appropriate, whether the test item will be performed on both cars.

Setting objectives

'The first point of preparation for a test session is to set out our objectives by gathering input from all the other stakeholders around the team whilst we're at the factory. By doing this, it'll quickly become clear that there is some work to schedule that's reliability relevant, some work that's race preparation relevant and some that is driver training, as well as benchmarking. I then have to ask myself how we are going to fit that all into the time available,' explains Wilson-Clarke.

The next thing to be clear on is whether the car needs to be in a certain mechanical configuration for the test to be meaningful. Certain aerodynamic tests would require specific bodywork to be fitted to the car, for example. Or perhaps the aim would be to test a particular kinematic configuration of the suspension. The team of mechanics must be involved in this conversation to know how to prepare the car in advance.

» The philosophy of testing hasn't changed much over the years, but the emphasis and time spent on real track testing is a smaller part of the decision-making process now

» Generally, on a per-car basis, we have more crew at test events than race events. At tests we often only have one car, but we need more capacity to analyse things live
Kyle Wilson-Clarke

Test sessions are always conducted to a strict run plan, with itemised objectives for each lap

A tyre test would also be pointless if there was no equipment packed to measure track temperature, for example. Thorough planning and communication are key. Generally, on a per-car basis, we have more crew at test events than race events. At tests we often only have one car, but we need more capacity to analyse things live. We have more instrumentation, and there's more analysis to be done,' comments Wilson-Clarke.

'Days are long, and time is precious, so we often have full 12-hour [regulation limited in Formula E] test days in which we try and minimise our down time as much as we can.'

Once at the test, responsibility is with the race engineer to coordinate the trackside team to ensure the car has the necessary fuel load and tyres fitted, and is in the right set-up, as well as ensuring the driver is comfortable and supported with whatever they may need. Then it just comes down to executing the run plan.

Achieving objectives

The run plan is a document created and managed by the race engineer, which itemises each lap of each outing and associates it with a particular objective. With the tasks mapped out, along with the durations and requirements for each item,

Special instrumentation is fitted to cars at test events. In this case, an array of Kiel probes to correlate laboratory / CFD data

Test sessions provide opportunities for car crews to practice working together in a live situation, but away from the more intense pressure of a race weekend

the race engineer has clear sight of every lap to understand how to instruct the driver and whether the session is running to schedule. If necessary, they will adjust the plan as the session progresses to ensure all objectives are checked off by session's end.

'When it comes to testing, we can do things like bring a suspension development, say, package a, b and c to test on the rear axle, which is predicted to give a net gain in x, y or z. We also aim to explore any predicted downsides and, if so, whether they are as bad as we think, or 10 times worse. Then, the work is to find a solution to offset any downsides and reduce the losses with each one to produce the largest improvement,' explains Wilson-Clarke.

Away from the intense atmosphere of the race weekend, testing sessions are also great opportunities for the crew to train and practice procedures and techniques for race weekends.

Pit stops and refuelling routines can be fine tuned, and team cohesion is broadened as the technicians and engineers spend time working together as a unit in a live situation.

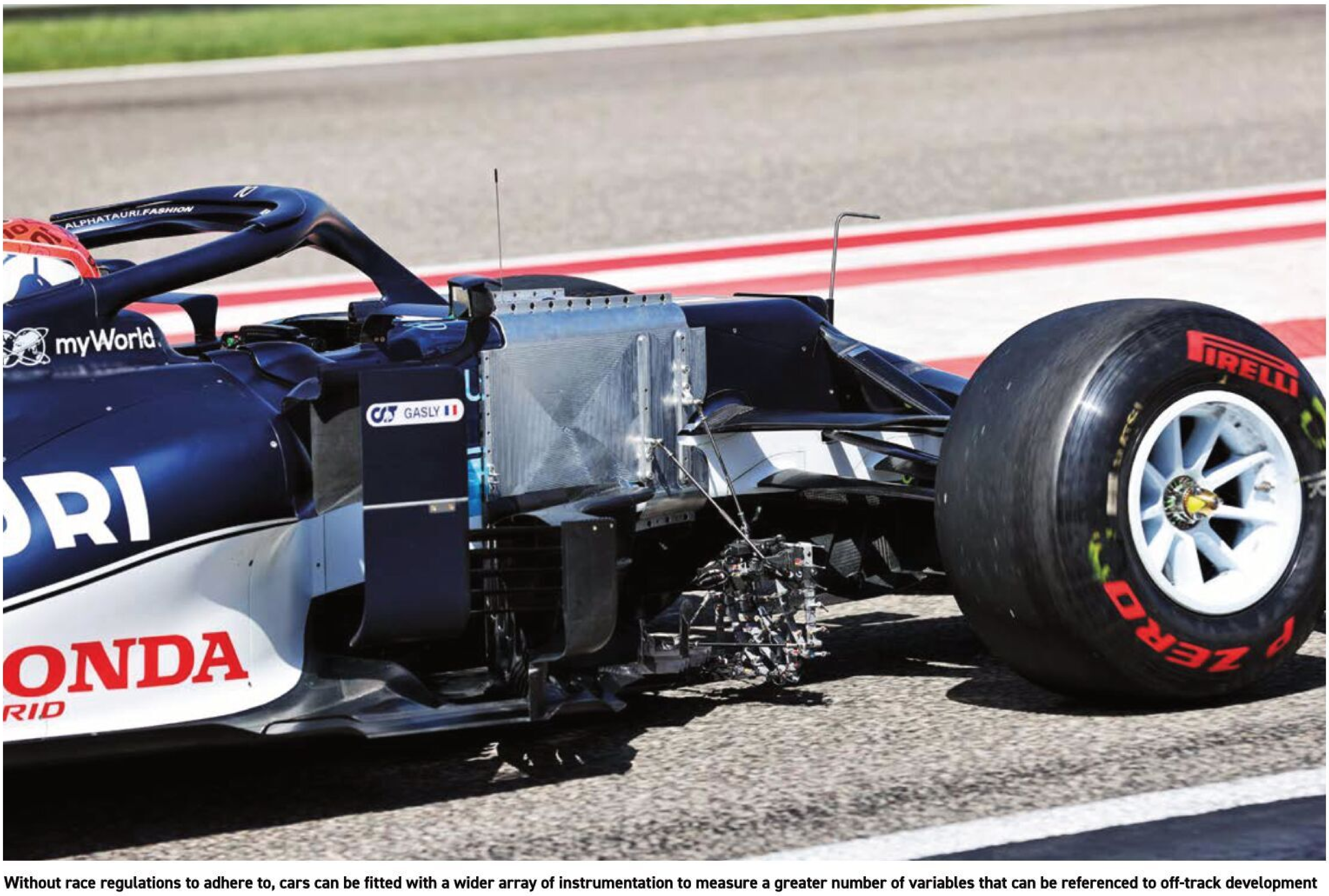
Making sure tyre changes are smooth, and minimising stop times with well-practiced procedures can win or lose races. If, over the course of an endurance race, you're doing 30 stops and losing two to three seconds a stop, that's a lot of time at the finish line. Practice makes perfect.

'As team principal, you become a little more of an observer at these sessions and find yourself spending time understanding how the team works. Perhaps you've introduced a new driver, perhaps new engineers, at the test, it's about being mindful of changes with car crews to be sure you're getting the best from the team,' adds Hughes.

Deeper understanding

Testing is a time where the car doesn't have to run within strict regulations, so teams often fit the cars with greater levels of instrumentation to measure a greater number of physical variables. This allows a deeper understanding of the car to be gained with reference to off-track development.

Test-specific instrumentation might include pressure scanning kit to understand pressure distributions over a wing



Without race regulations to adhere to, cars can be fitted with a wider array of instrumentation to measure a greater number of variables that can be referenced to off-track development

surface and learn about separation in more depth, or infrared arrays to monitor temperature distribution across the contact patch to understand how the tyre reacts to the energy input over a lap.

Likewise, additional fluid pressure sensors and thermocouples might also be fitted to key areas. A lot of extra engineering value can be gained from test sessions.

Laboratory testing is not always a reliable representation of real conditions, so test sessions are often the first opportunity teams have to test new technological innovations live. Many ideas can look great on paper, but they might not work with the car holistically in practice. Furthermore, the driver may not be comfortable with the impact on the wider performance of the car.

'Many years ago in F1 we tried automatic downshifting,' recalls Hughes. 'This was something that looked very good on paper in terms of gearbox control and had a positive impact in terms of reliability of gearbox components. In reality, though, during tests we got very different results between the two drivers depending on their driving style. Technically, it offered better control in terms of corner entry but, ultimately, it took away a level of driver control, which wasn't enjoyed. That was something that came off the car as quickly as it went on.'

Digital testing

With most championships now heavily regulating the amount of in-season track testing a team is able to undertake, off-track and digital testing methodologies have started to take precedence.

Wind tunnel tests, DiL simulations, lap time simulations and other analytical development methods are now regular features on in-season test schedules, but there is still no replacement for real track time.

Laboratory tests and mathematical models will never replicate real-world conditions 100 per cent, and there are *always* discrepancies in the data that don't line up to physical reality.

Data measured at track tests is therefore used to feedback into the software-generated data, or data recorded from laboratory testing, for comparison to improve accuracy, resolution and coherence of the simulation environment.

This process is known as correlation, and enables adjustments and alterations to be made to digital and laboratory models to improve results. It is invaluable if you are to trust all the intensive work the rest of the engineering team is doing off track at HQ.

We've all heard stories of Formula 1 teams trying new aerodynamic components straight from CFD, only to find the perceived gain in performance just wasn't there at all, so consequently having to hastily revert

Wilson-Clarke won Le Mans with Porsche in 2017 having previously won with Audi

» What we see on track at race events is only the tip of the iceberg of what can be years of development and fine tuning through the process of testing

to old specifications. Given the freedom of physical track testing current regulations prevent, these parts would never have made it to the race event in the first place.

Driver input

Drivers are an integral part of a car's performance, and a major consideration in test events for their ability to feedback and influence the reliability of data. Some teams even have development drivers specifically for this purpose.

In order to collect reliable data, it's important for test conditions to be consistent and stable. Drivers at test events therefore need to be given clear objectives and be able to communicate reliable feedback to the race engineer on the car's limitations.

To do this, driver input needs to stay consistent throughout the outing. This allows assessments of variables to be made from one lap to another, and confidence in the data amassed. In other words, comparing apples with apples.

Perhaps the clearest advantage of this is with comparisons of different tyre compounds or brake pads. A driver who can put the same energy into the components through delivering consistent laps over multiple stints offers a much better comparison than a more erratic driver with a wider distribution of lap data.

'Certain drivers can be better in certain scenarios,' notes Wilson-Clarke. 'For example, I worked with a couple of drivers in LMP1 tests who were very good at delivering consistent laps whilst feeling the smallest of adjustments. When we were doing tyre tests this was ideal as they could lap very repeatably and we'd get really good information in that sense. Testing is about using the best tools you have, and drivers are a part of that tool kit for sure.'

Not all test drivers are racing drivers, so this must be taken into consideration during correlation from a test to a race.

The test schedule therefore must be integrated well in advance of the start of the season, particularly with reliability testing.

If a failure does present itself, the design team must first understand *why* the part failed, then they must re-design it, manufacture it and test it again before it can be signed off ready to race. The lead time for improved parts can sometimes mean testing for the season ahead can start during the current racing season.

'In terms of championships and races like Le Mans, we were hitting the track for testing towards the end of one season in order to sign off parts for Le Mans the year ahead,' concurs Wilson-Clarke. 'We'd have to test from September onwards in parallel to the current season.'

What we see at races is only the tip of the iceberg of what can be years of development and fine tuning through the process of testing. Although the focus may have shifted to digital over the physical kind by regulation, and due to speed of development and new technology, it's still all about learning, and the same philosophies apply.

'Test sessions are where you learn about the car, the driver and how to optimise the performance of both. Racing is the icing on the cake in terms of all the hard work that goes on behind the scenes. It's where you put everything you've learnt through testing into practice in the hope of getting the very best out of the car,' concludes Hughes.

The fundamentals of testing, and what you need to accomplish to make the car reliable and perform optimally in a race, haven't changed, so track testing is going to be here for a while longer, albeit in different forms as the sport and the science evolves. ●

The WEC prologue often provides the first opportunity for fans to see the new Le Mans cars

The all-seeing eye

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

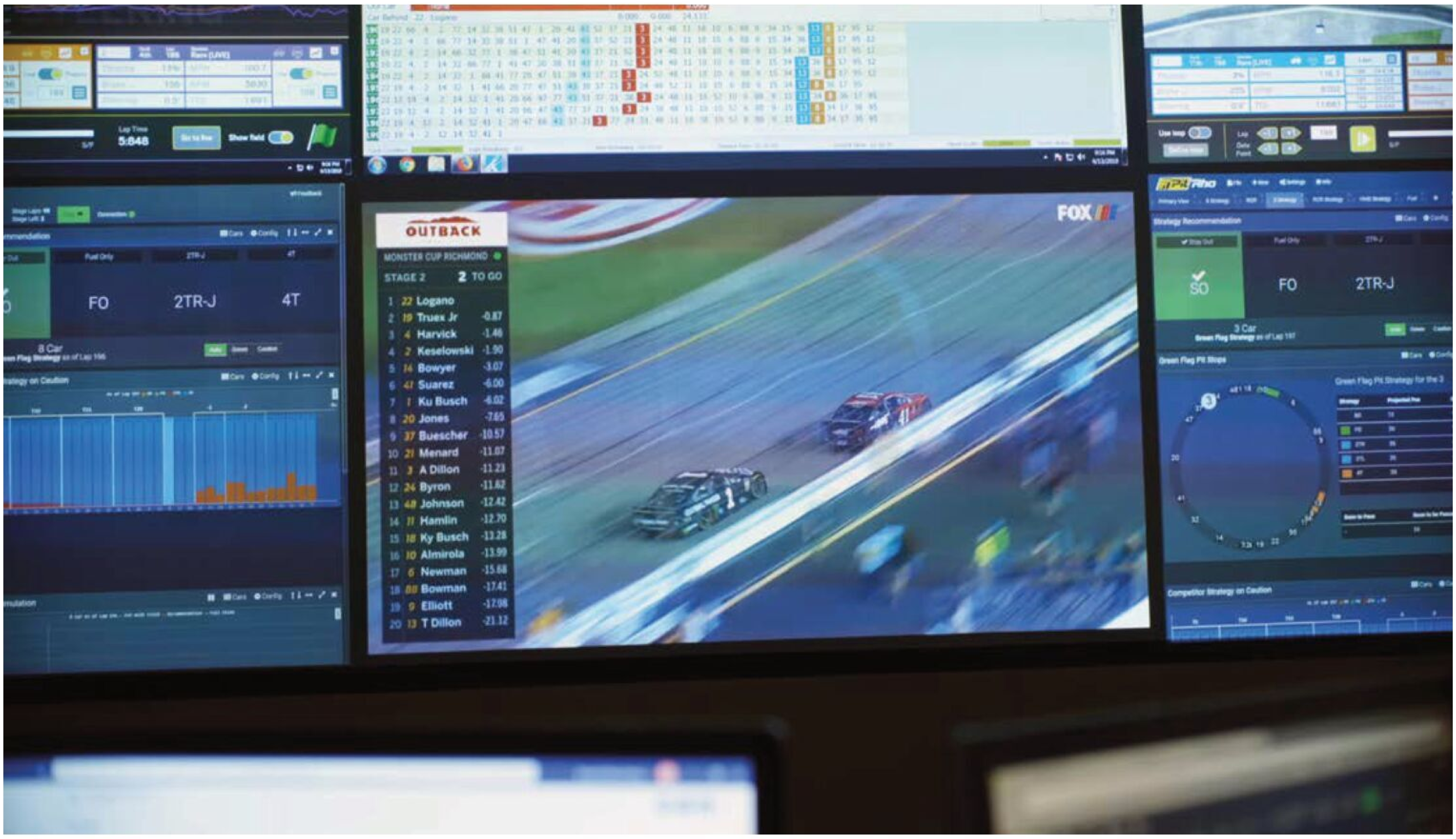
» The final calls on strategy still rest with the crew chief, but they are now backed up with considerable engineering resource

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

By LAWRENCE BUTCHER

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

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



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

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

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

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

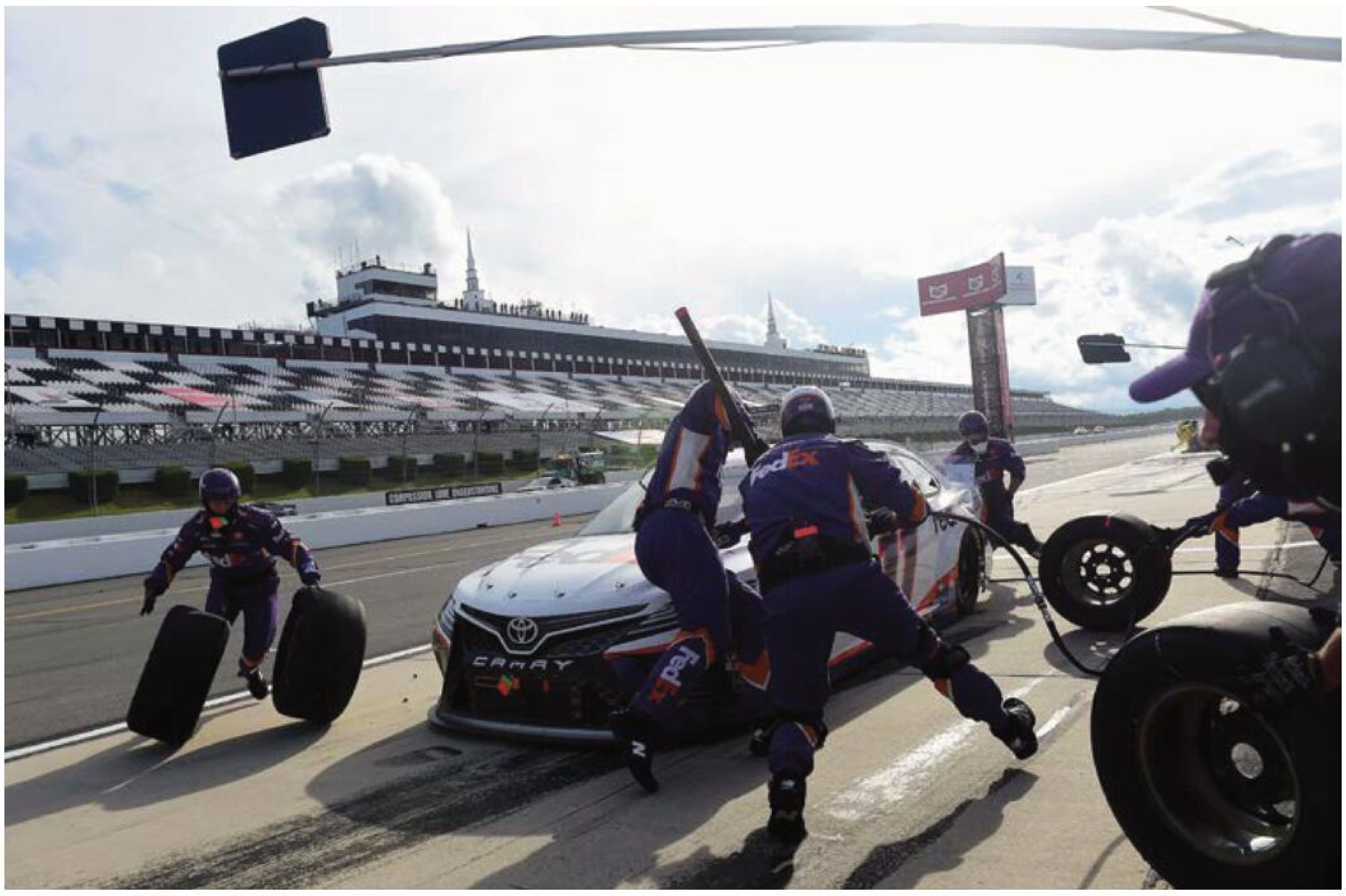
Racing roots

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

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

'Some of us in the Vehicle Dynamics Group got to go over quite a bit,' he recalls. 'One of the things we saw, which is likely ancient technology now, was their method for predicting the outcome of a race. Starting from the first practice laps, based purely on lap times and sector times, and then refining the projections lap by lap.'

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

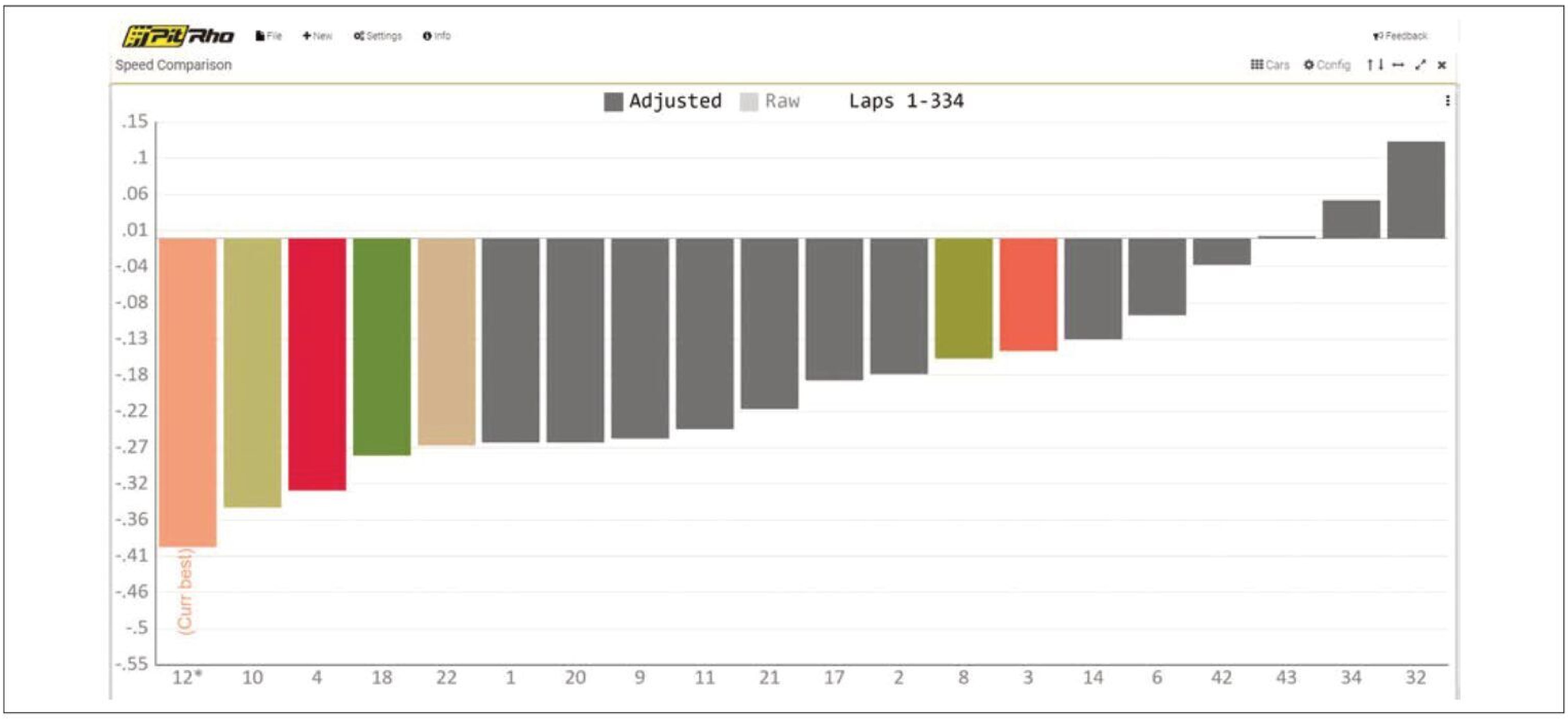


Calling a pit stop strategy incorrectly can lose a race for a fast car, but get it right and it can push a slower car up the field

» A more competitive field, longer races, and a lot of full-course cautions… add an element of statistical chaos to any modelling work

Josh Browne, Rho AI founder

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



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

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

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

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

An academic interlude

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

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

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

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

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

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

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

Data integration

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

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

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

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

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

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

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

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

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

Significant features

Key to making the system work, and drawing on what is now 18 years' worth of data, is identifying which features of the data are most significant. 'We have to understand the dozen or so features that really matter, and then allow the system to learn those features as a race evolves,' concurs Browne. 'For example, we might identify that if you restart on the front row, in a car that is only 15th on speed, on older tyres, you can still win the race, because the adjusted speed from first to 15th might only be 0.15 seconds a lap, but it is worth 0.18 seconds a lap to start first.

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

'We actually won with Austin Dillon at Texas in 2020 doing just that. It was because by that point in the race, we precisely understood the dynamics around lap time degradation, traffic density, everything.'

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

The unusual situation around the 2020 season, where the impact of Covid meant that there were no practice sessions before races, placed an even greater onus on Pit Rho's algorithms, as Browne notes.

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

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

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

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

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

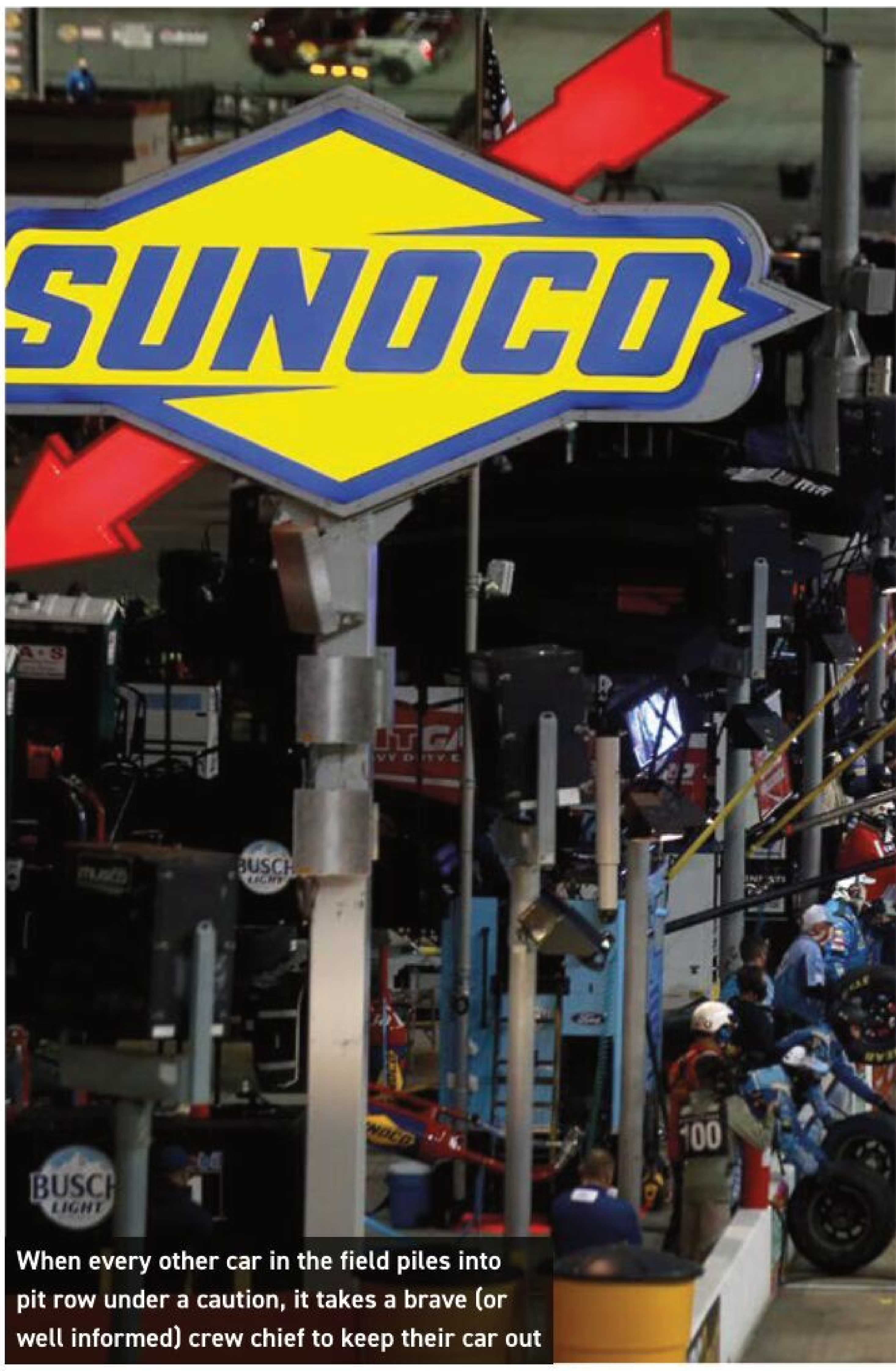
The top drivers tend to be quite adept in this area, knowing not to waste time battling to keep someone behind to the detriment of overall race position. However, he notes the one exception was every driver in the field used to slow down to pass Danica Patrick, even those usually unphased by passing.

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

» As soon as the green flag drops, we start learning

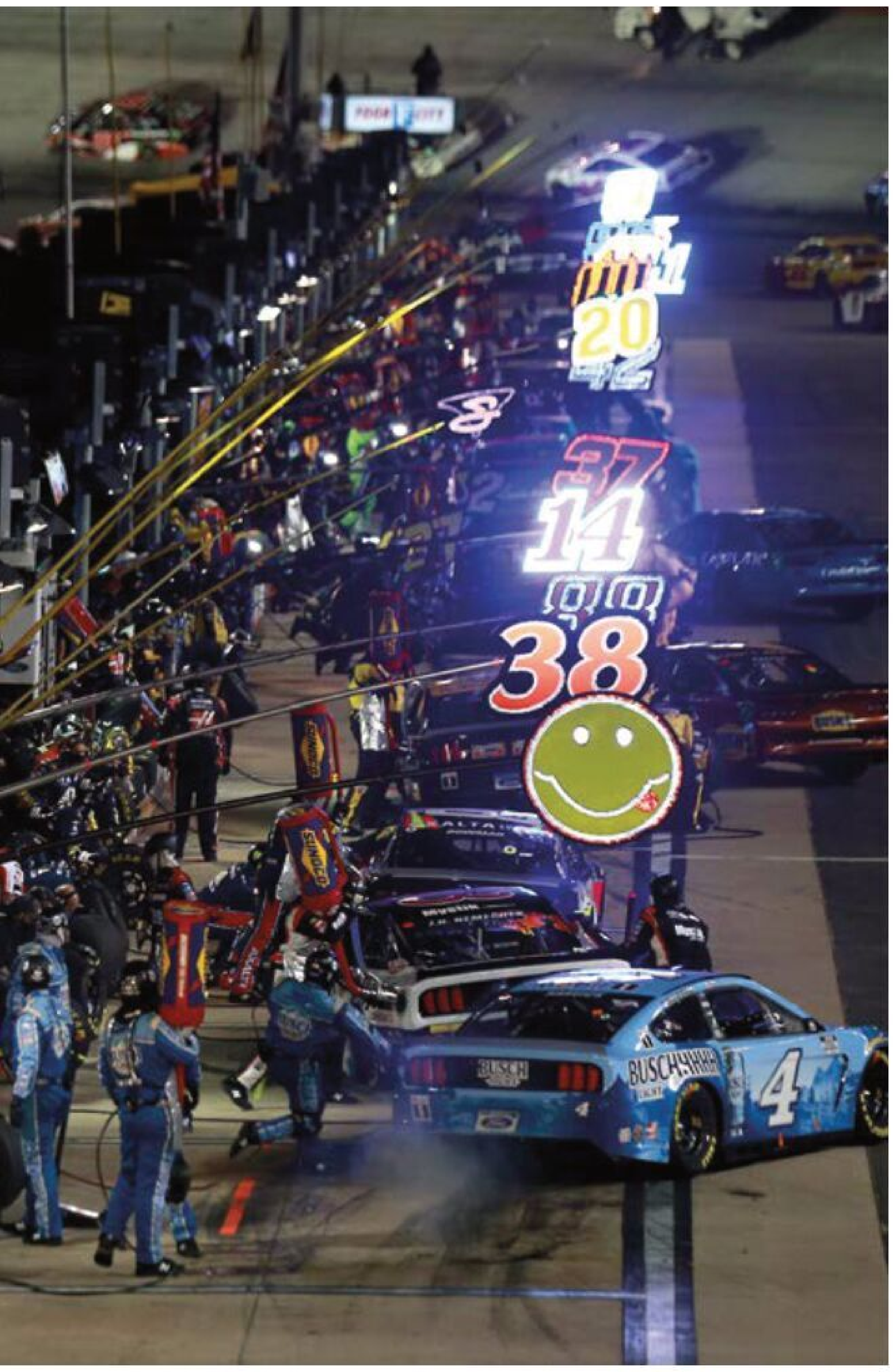
Old school acceptance

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



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

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



The crew chief's view

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

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

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

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

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

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

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

receptive to the power of data-driven strategy. 'You could probably place Chad Knaus in that 'old school' category, but he was a huge supporter of the system, because he knew the difficulty in making all of these decisions in real time.

Intelligent experts

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

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

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

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

Points mean prizes

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

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

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

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

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

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

» No matter how much data you have, or how much you *think* you know, rubber will always prove you wrong

Wearing thin

Accurately predicting the changing behaviour of tyres is key to winning races, yet it's a science that continues to baffle engineers

By GEMMA HATTON

Understanding, measuring and minimising tyre degradation is the golden ticket to race wins and championship trophies across the spectrum of motorsport. Yet, despite some of today's teams being equipped with entire departments of tyre engineers, and having access to advanced, real-time tyre models, the behaviour of tyre degradation baffles them.

This is predominantly due to the viscoelastic nature of rubber. A viscoelastic material is one which exhibits a mixture of recoverable elastic deformation and permanent viscous deformation. In other words, once rubber has been deformed and the load removed, it returns to its original shape, but only after a period of time. This time, or lag, between when the load is removed and the rubber returning to its original shape is called hysteresis, and during hysteresis a portion of the supplied energy is dissipated as heat.

The behaviour of rubber depends on the duration of this hysteresis, the amount of heat generated during the process and the rubber's modulus. However, these three attributes also vary with stress frequency (the amount of times the rubber is stressed) and temperature. So in motorsport, when tyres are subjected to continually changing loads and temperatures, you can start to appreciate the complexity of tyre behaviour, and how difficult it is to accurately predict.

Generating grip

Now we understand a bit about the behaviour of rubber as a material, next we need to understand how tyres generate grip. This is done in two main ways: molecular adhesion and indentation. As the name suggests, adhesion occurs at a molecular level where, as the tyre rotates, the rubber molecules bond to the track and are then stretched. The rubber's viscosity resists this deformation, which generates a friction force. The bond is then broken, and the rubber relaxes, ready to bond again.

Indentation, on the other hand, is where the roughness of the track 'excites' the rubber and, as it doesn't return to its original shape, this asymmetrical deformation generates a friction force. Overall, a rubber's flexibility and hysteresis help generate the friction forces that produce grip, and rubber exhibits maximum hysteresis and suitable flexibility when it is close to the glass transition temperature. This is why tyre temperature is so vital when understanding degradation.

Unfortunately, measuring tyre temperature presents another conundrum because, ideally, you want to measure the bulk temperature, which is in the centre of the tyre. But until sensors are developed that can measure *through* rubber, only the carcass temperature can be measured. This is currently done through a TPMS (Tyre Pressure Monitoring System) sensor mounted directly onto the wheel rim where an infrared (IR) element measures the temperature of the underside of the carcass.

Measuring temperature

The tyre's surface temperature can also be measured using infrared sensors that, in F1 for example, are mounted either on the front wing or on the rear floor. These measure the distribution of temperature across an array of points on the surface of the tyre.

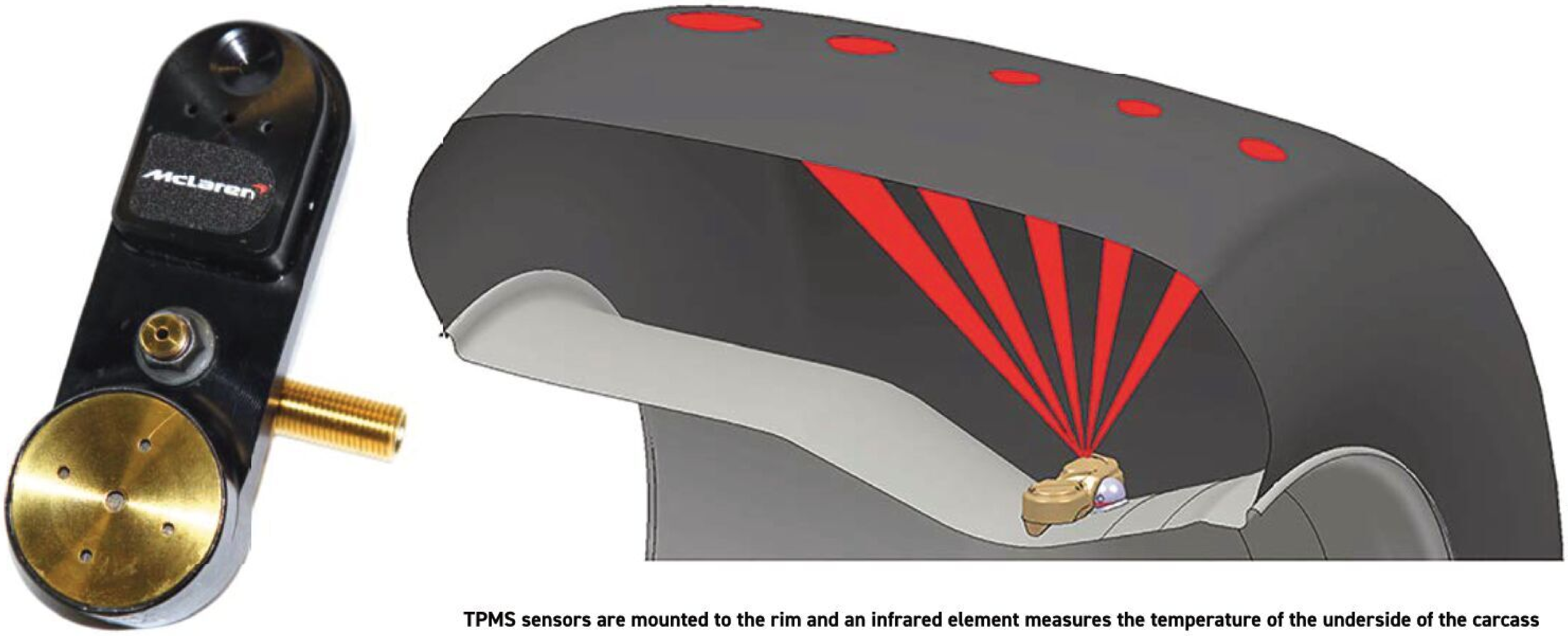
IR guns and hand-held probes can also be used to measure surface temperature. Although this gives a good indication of when the surface is overheating, it can be a misleading metric. For example, whenever the tyre slides, or experiences a flat spot, this will cause a spike in surface temperature but have minimal effect on the bulk. Therefore, when determining the thermal state of a tyre, engineers either rely on the carcass temperature, as this is closest to the bulk, or calculate bulk temperature, which is what Formula 1 teams do.

'There's a million different ways of measuring the bulk temperature, and every team will have its own way of doing that,' reveals Jody Egginton, technical director at Alpha Tauri. 'We'll know the gas temperature, carcass temperature, surface temperature and the rim temperature. From amongst all of that, you can derive a bulk temperature. So essentially you take those four measurements and come up with a metric.'

> **» The specific behaviour of rubber depends on the duration of this hysteresis, the amount of heat generated during the process and the rubber's modulus**

Once the bulk temperature has been defined, teams can then start to understand whether the tyre is within its optimum working range. This is essentially the window of bulk temperatures where a tyre generates the most grip. Keeping the tyres within this window is the challenge. As a racecar drives round a track, each of the four tyres are loaded differently, and consequently have different variations in bulk temperature.

However, the nature of each circuit plays a major role in tyre temperature and consequent wear. In F1, high-speed, long-duration corners subject the fronts in particular to high lateral loads, which overheats the surface, often leading to graining. This is why the front left suffers such high graining and wear at Silverstone. While circuits with lots of lower speed, sharp corners lead to the rears overheating as drivers subject them to high longitudinal loads when they accelerate out of corners.



bf1systems

TPMS sensors are mounted to the rim and an infrared element measures the temperature of the underside of the carcass

The trick is to balance the grip across the axles to achieve a stable car that the driver can handle. The moment there is a loss of grip, the car will either understeer or oversteer and the tyre will be dragged across the track, which will induce surface and / or thermal degradation.

Graining is a common sight in most motorsport categories and indicates the surface of the tyre is overheating. The consequent radial ridges produced reduce the contact patch between tyre and track, reducing available grip

Types of degradation

'There are two, potentially three, types of tyre degradation, and each type has different subgroups depending on where you are with the car,' explains Egginton. 'Firstly, there's wear degradation where you are simply wearing the rubber [on the tyre surface] away. As you do that, tyre adhesion reduces and there's less rubber available to generate heat, so it's more difficult to keep the tyre within the correct thermal state.

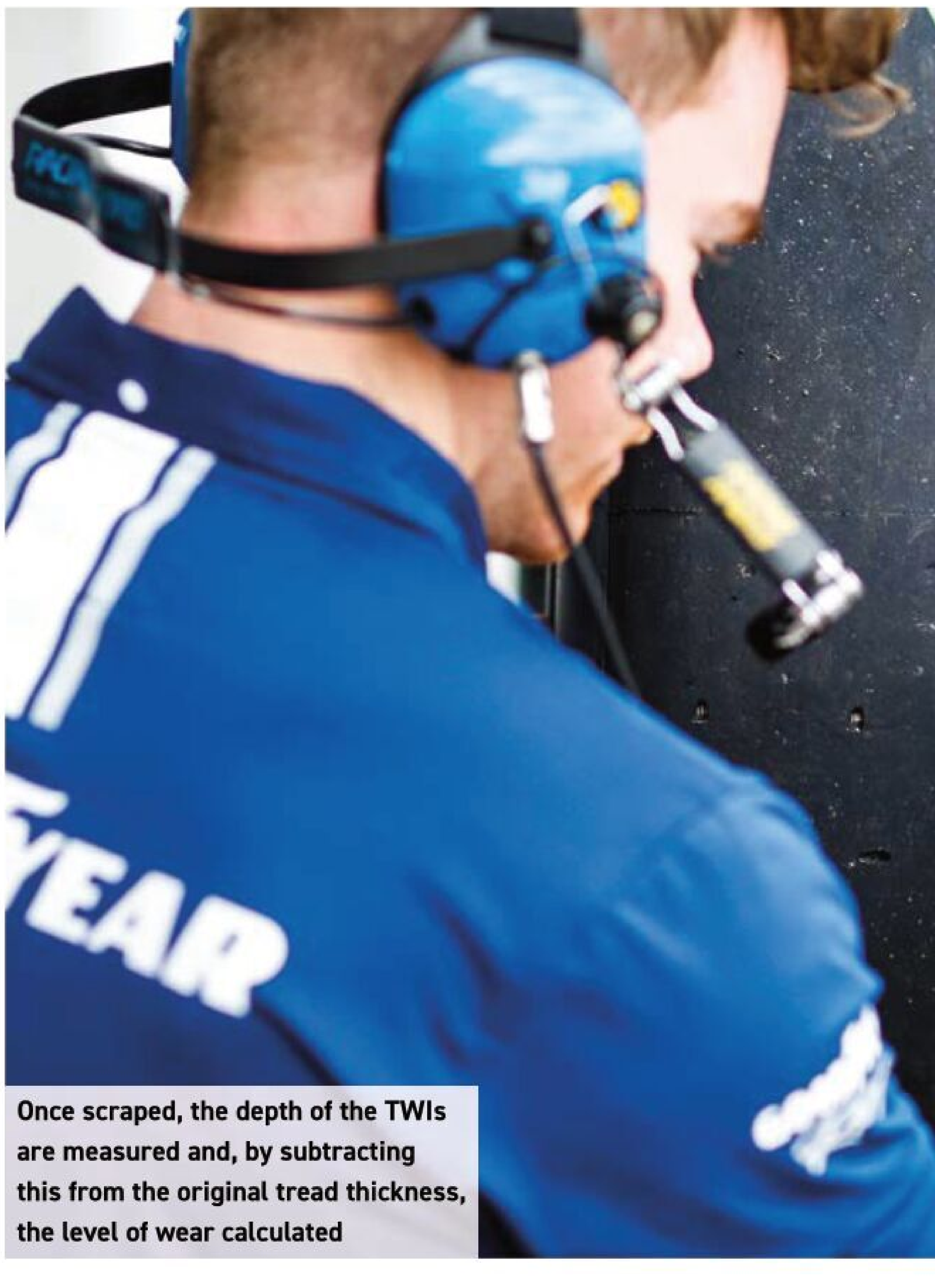
'Then there's thermal degradation where you're overheating the tyre, so it's not operating within its optimum working range. In some respects, that's also linked to a third type of degradation, which is chemical, because the composition of the rubber compound itself is also degrading.'

Surface or wear degradation can manifest itself in several different ways, but each results in surface damage, which reduces the contact patch area, leading to lower overall grip. The most common type is graining. This is where the tread heats up more than the carcass of the tyre and small sections of rubber begin to break away from the main compound. Due to the lateral force exerted, these rubber particles are then rolled across the surface and re-stick to the tyre, creating wavy ridges towards the outside of the tyre. Graining can also occur when the tyre is cool, known as cold graining. This is where the tread is too cold and the outer layer effectively shears away from the main body of the tyre as it slides, causing narrower and linear ridges.

Then there is blistering, which is where the middle of the tread effectively reaches the boiling point of the rubber and small bubbles begin to form. If the temperature continues to rise, these bubbles explode, rupturing the surface of the tyre and leaving holes of boiled rubber. Blistering is more common in F1 and usually occurs along the centre of the rear tyres and on the inner shoulder of the front tyres as this is normally the hottest area.

As rubber generates its own temperature through hysteresis, the thicker the rubber, the more heat it generates and so the likelihood of hot spots increases. Interestingly, this is why harder compounds can sometimes suffer more from blistering, because they

Tyres have a series of tread wear indicators (TWI), which are different depth holes used to measure the wear of the tyre. But before they can be 'read', any pick up has to be heated and scraped off



Once scraped, the depth of the TWIs are measured and, by subtracting this from the original tread thickness, the level of wear calculated

Blistering, where hot spots within the tread form bubbles that explode and rupture the tyre surface, often occurs on the centre of the rear tyres and on the inner shoulder of the fronts as this is where the tyres are hottest during use

» Wear is non-linear and varies across the width of the tyre due to the variation in pressure experienced throughout the contact patch

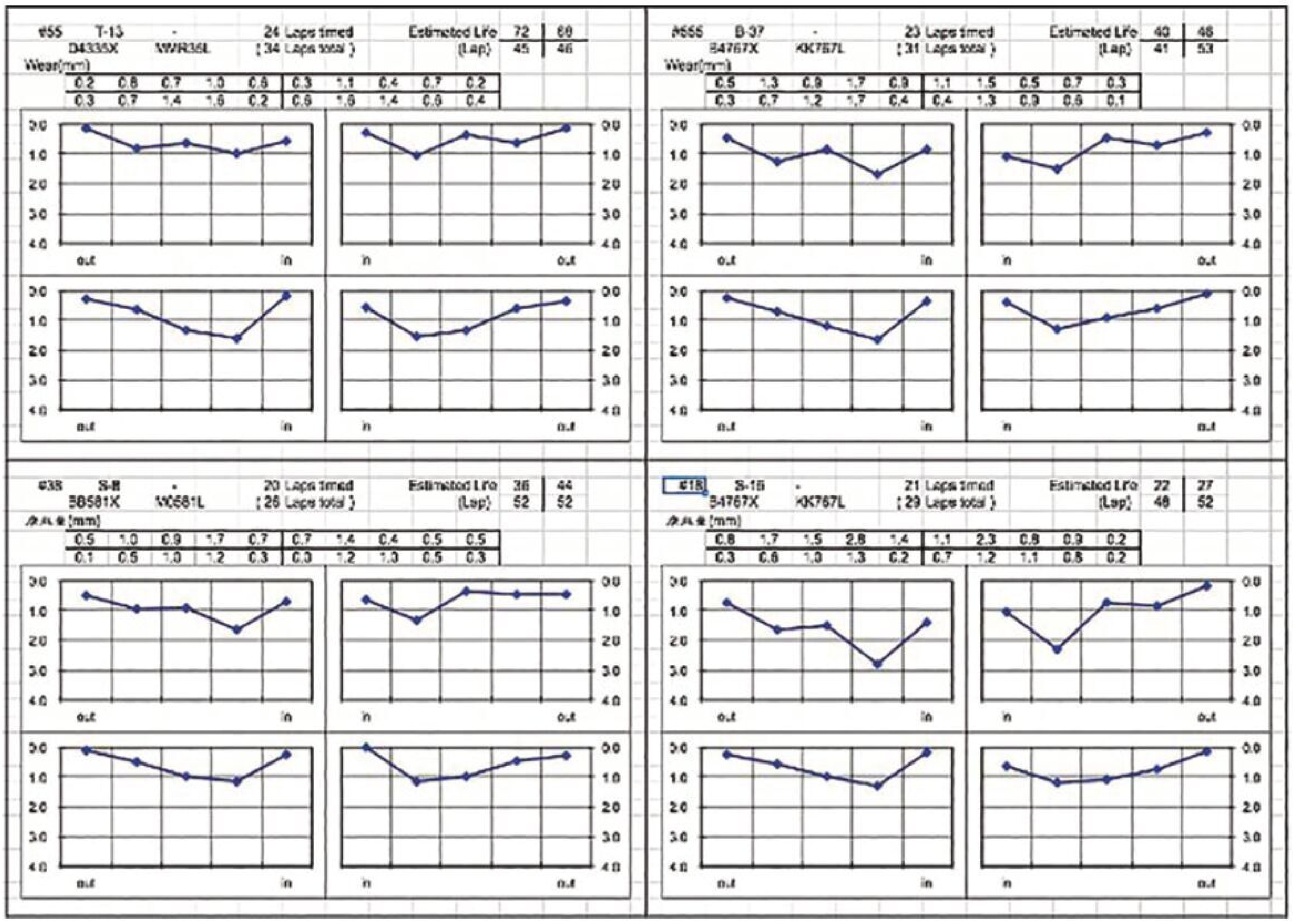
have lower wear rates, which means there is more rubber to overheat.

Both blistering and graining result in the removal of rubber, and so can quickly wear out sections of the tyre. But even when there is no evidence of surface degradation a tyre wears, which is why the track 'rubbers in', and why we see marbles on the side of the track. Less rubber means less heat generation and so, as the bulk temperature decreases, so does grip, which then leads to sliding and further wear and the cycle repeats. This is often referred to as the 'cliff' and is the stuff of nightmares for every driver and team alike.

The nature of wear

Unfortunately, like all things with rubber, wear is non-linear and varies across the width of the tyre due to the variation in pressure experienced throughout the contact patch. Consequently, tyre wear not only differs for each corner of the car, but also depends on the type of compound, the nature of the circuit, micro and macro roughness of the track and ambient and track temperatures. In some cases, wear can be so extreme that a tyre can wear right down to the belts.

'If you run a completely worn tyre, you expose the construction. In that case you take a lot more risk because the construction is not protected by the tread,' explains Mario Isola, head of F1 and Car Racing at Pirelli. 'If you then hit debris, or hit a kerb, you take the risk of damaging the construction. If you do that, particularly in high severity circuits, it's easy to have a loss of air and then a deflation where you have to stop the car.'



The result is a wear profile that illustrates the amount of tyre consumed at each TWI, for each of the four tyres on the racecar. The wear pattern of four different sets of tyres are shown here

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Tyre pressure is another factor that affects degradation because it changes the size of the contact patch. In F1, Pirelli prescribes minimum starting pressures, so all teams leave the box with the same tyre pressures. As the tyres warm up, pressure increases, and the tyres effectively 'balloon', resulting in a much smaller contact patch. However, high running pressures strengthen the sidewall and help maintain tyre integrity, which is why Pirelli will often increase its recommended minimum starting pressures after Friday running.

Pressure evolution

'Having a higher pressure obviously helps the construction but, on the other side, there is the risk of more overheating, and in some cases a bit more blistering because of the reduction in the footprint area,' confirms Isola.

So, on one hand you have the tyre manufacturer boosting pressures, resulting in a smaller contact patch, while, on the other hand, you have teams trying to reduce pressures and maximise contact patch size.

'The curveballs come when they [Pirelli] up the minimum pressures,' says Egginton. 'The more air they demand you have in there, the further it probably takes you away from the optimum operating range of the tyre. So we try to minimise the pressure evolution using techniques like rim cooling, which will change the way the tyre operates.

'Normally, you want to run the fronts as cold as possible. If you run anything else it's difficult to manage the bulk temperature.'

Tyre modelling

Given all these variables, how *do* teams predict and manage tyre degradation? Well, first they try to model it, but generating reliable, accurate tyre models is very difficult.

'We have a baseline tyre model and we will change some of the settings based on Friday data. Or, if we don't feel we've learnt anything representative, we'll leave the historical data in the model,' explains Egginton. 'We then apply our normal offsets and variables based on temperature, track evolution… all the boring stuff.

'In the race, the model updates constantly. Pace is a big factor, of course, so we're constantly manipulating that but, if the driver doesn't listen to instruction, we'll see directly what's going on with tyre wear and energies.

'So we're instructing the driver based on a live model and how far we think that tyre will go. If we have a view on how far it needs to go, and we're not getting there, we either change strategy or react accordingly.'

One of the key metrics used in tyre models is tyre energies. This is a much more reliable way of calculating the available performance because it incorporates the effect of sliding into the wear calculation.

You can assume a tyre leaves the garage with 100 per cent energy and the amount of slip measured by slip angle sensors, along with corner severity, wears the tyre and consumes that energy. You can then forecast whether the tyre will have enough energy to last to the end of the stint and can employ strategies to manage tyre life.

Differing strategies

'We get very excited about tyre energies as they are an important part of determining where we are with tyre life,' says Egginton. 'Based on what that tells us, as soon as the tyres stabilise, we might tell the driver to tyre manage in high-speed corners, conduct more lift off in certain areas, be more careful with tyre slip when exiting a low-speed corner or be careful with the brake moment balance.

'That metric gives us the ability to try to manage the energy and the slip and tells us if we're doing the right things to have enough tyre until the end of the race.

'We effectively drive to targets derived from the model. The driver is just validating the model. We'll only ignore those targets if fighting for points, or the driver is struggling.'

» We get very excited about tyre energies as they are an important part of determining where we are with tyre life

Jody Egginton, technical director at Alpha Tauri

Tyre models have therefore become a vital tool when managing tyre degradation, but the specific strategies can vary dramatically between different types of motorsport.

'One of the big differences between endurance racing and Formula 1 is that in endurance racing, the primary focus is achieving the least amount of degradation possible, not necessarily peak performance, because it's not sprint racing,' highlights Mike McGregor, manager of sales, testing and track support at Goodyear. 'In some races, we do over 700km on a single set of tyres, which is around three Formula 1 races. Our target at Le Mans, for example, is four stints, and we design the tyres to be as consistent as possible throughout that distance.'

One of the tricks tyre manufacturers use to manage degradation for different circuits and conditions is to design a range of compounds, selecting the most appropriate to avoid overheating issues. 'Generally, we step the compound range up and our range is designed so that, in theory, we can always go to the stiffer compounds to avoid overheating issues,' reveals McGregor. 'The stronger and stiffer compounds generally have more thermal stability than the softer compounds. So we can run the softer compounds at Le Mans at night. But if you were to try and run that in the true heat of the day at Silverstone then, yes, you might suffer from overheating.

'But we tend to recommend compounds so before we even get to that position, we're running a slightly stronger tyre.'

Some forms of tyre degradation can actually be recovered from. For example, light graining can be worn through, removing the ridges to increase contact patch and grip, but this usually only works for a short period of time before the tyre begins graining again.

Surface overheating can also be reduced by driving technique, such as lifting off through high-energy corners and controlling slip, along with adjusting brake balance, rim cooling and improving overall car balance.

» The stronger and stiffer compounds generally have more thermal stability than the softer ones

Mike McGregor, manager of sales, testing and track support at Goodyear

Rallycross tyres

Each category of motorsport demands a different type of tyre, and one of the most brutal environments a tyre has to endure is that of World Rallycross (RX). Supercars that boast 600bhp run on a mixture of asphalt and unsealed (gravel) surfaces, complete jumps that are 2.0m high and accelerate from 0-60mph in 1.9s, which is faster than F1. These extreme longitudinal loads require a robust tyre with an extremely strong construction.

'It all comes down to the way you lay up the plies of the tyre to achieve a construction that can withstand the loads during jumps, starts, impacts and kerbs,' explains Matthew Vincent, materials development manager at series supplier, Cooper Tires. 'The sidewall in a World RX tyre has some additional reinforcement in it, and even the compound we use in the sidewall itself has to be specifically tuned for abrasion resistance because there is a lot of contact and rubbing on the sidewall.'

Unlike most GT and Formula tyres, Rallycross tyres have a very wide working temperature range because there are no tyre ovens or blankets. Therefore, the tyre has to be able to work straight from the standing start at ambient temperature.

'We use a control tyre in World RX so there's only one compound of dry tyre throughout the whole season,' says Vincent. 'The calendar means track temperatures can vary from 5degC to 40degC, so the working range has to be broad. Normally, the optimum temperature for the compound is anywhere between 70degC and 120degC.

'Despite each race only lasting for five or six laps, these tyres generate a significant amount of heat and it's not uncommon to see tyre temperatures rise to above 120degC in hot conditions.

'This is where the gravel sections of track really help. Because they are lower grip, it gives the compound a chance to cool down. If the track was all tarmac, we'd probably find the compound getting too hot and dropping out of the optimum performance window.'

Thicker treads

This high heat generation is partly due to the thicker treads run in rallycross tyres, around 8-10mm, compared to GT tyres, which are approximately 4mm thick. Interestingly, despite these thicker treads and high temperatures, blistering and graining are not a problem in World RX, so the only degradation teams have to manage is wear. These wear rates mostly depend on the nature of each circuit, as well as each team's unique set-up.

'Historically, some tracks had extremely high wear rates. This was predominantly down to the nature of the surface,' explains Vincent. 'Now, the modern materials used to generate the unsealed surfaces wear in a more consistent and even way. So you'll get a gradual drop in the coefficient of friction over the weekend, but the track doesn't wear like it used to, or suffer from rutting.'

World RX tyres have to work in ambient temperatures between five and 40degC, operating temperatures between 70 and 120+degC and be able to withstand a brutal working regime

» The only degradation teams have to manage is wear

Rallycross tyres also need to cope with a wide variety of set-ups because teams are relatively unrestricted when it comes to suspension design. The GCK Megane cars, for example, feature a radical suspension layout with inboard brakes. Surprisingly, despite this diversity, the running pressures of World RX cars are similar because all teams are trying to run the lowest pressures possible for a grip advantage at the start.

'The danger when running low pressures is, if you hit a kerb in the first corner, you could knock the bead of the tyre off the rim, so we've done a lot of work over the years on bead design to avoid that,' says Vincent. 'The teams are pretty good at knowing what the limits are, and so run sensible pressures. It also depends on how they want the car to drive as some drivers like a soft set-up.'

As with most championships, the future seems to be electric and with Projekt E having taken off during 2021, there are even more factors to consider. 'It will be interesting to see how much the cars vary in the electric championships,' says Vincent. 'Projekt E runs on our ACB11 tyre, but with electric cars you have to consider the extra weight and additional torque. So we may have to increase the strength of the case, or maybe develop a wider tyre in the future.'

'The influence of the driver should not be underestimated,' admits Egginton. 'These guys are quite good at managing tyres. They can implement a small amount of lift off and, if split up correctly in the right areas around the track, you can do it without losing lap time. That's quite a nice trick for bringing tyre and brake temperatures down.

Driver influence

'A lot of what is said over the radio [during a race] has already been discussed, so the drivers know what deltas to drive to. That way, when you switch to plan b – provided they remember of course – they will adapt the tyre management to make sure the tyre lasts for the new stint length.'

Educating drivers is particularly important in endurance racing where driver ability and experience can be very varied. Key to a good stint time, rather than a lap time, is not to lock up a tyre, particularly in the first of a multiple-stint run but there is more to it than that. Working the tyre properly through a variety of temperatures and track conditions is also critical and to achieve that engineers have a lot of educating to do. 'One of the big things we've worked on over the last 10 years is driver KPIs,' says McGregor. 'In endurance racing, you have a mixture of drivers from full-time professionals to gentlemen drivers, so we try to work with them as much as possible to manage things like steering input, brake regression and throttle regression so they're not overdriving the tyre in critical areas. It's all about managing the performance of the tyre and deciding when you put it into the tyres.'

In conclusion, no matter how much tyre data you have, or how much you *think* you know about how a tyre will perform on any given track and condition, racing rubber will always prove you wrong. ●

A nice bit of kit

A round up of the latest developments in pit lane equipment and technology

By Sam Smith

Success in motorsport is about so much more than just the talent and feel of a driver, or the technical and strategic skill and guile of the engineers that run them.

Strength in both human knowledge and good hardware is central to any well run team. From set-up patches to tyre guns, from refuelling rigs to bodywork stands and communications equipment, the level of detail is almost forensically excellent at the upper echelons of the sport today.

Teams spend so much time and money on engineering the actual car and pouring over drivers' delta times, or nuances that can provide the vital hundredth of a second, that leaving anything to chance is neglectful.

From the pit entry line to pit exit, any time that can be gained on competitors means that shrewd choices in the equipment used, and how team members use it, is now a competitive advantage of its own.

XPB

Jacks and stands

Bespoke, quick lift jacks are commonplace in pit lanes these days, with spring-loaded devices including stainless steel mechanisms and aluminium skates that bear little resemblance to those used in home garages.

Lifting cars via a manual or on-board jacking system is important in the garage and on pit lane

Some of the leaders in supplying these are Peterborough, UK-based Greaves 3D engineering, which was born out of the successful Sportscar team, Greaves Motorsport, founded by driver and entrant, Tim Greaves.

Greaves' son, Jacob, now spearheads this specialist company that supplies teams with a host of pit equipment, and also acts as a certified Paoli wheel gun servicer.

The world of endurance racing is the ultimate test for many of the products companies such as Paoli and Greaves offer.

One of its former competitors in LMP2 racing is JOTA, which has an enviable record of two category wins and a host of podium appearances at Le Mans.

» Shrewd choices in the equipment used, and how team members use it, is now a competitive advantage of its own

Paoli Typhoon is a model sold primarily for use by technicians in Touring Car series

Paoli DP 3000 Supersport wheel gun, designed for use in Grand Am, GP2 and DTM

Paoli DP 36 SF EVO is another model in the company's inventory aimed specifically at the Touring Car market

Images: Paoli

So critical is the pit stop to top-end motorsport these days that an entire industry has developed around finessing the tools and equipment used by the crew

» **Teams have rapid prototyped and 3D printed extended trigger mechanisms so hands can be closer to the [wheel] gun**

Its team has expanded significantly in recent years, and in 2021 ran dual programmes in the FIA World Endurance Championship and the Fanatec GT World Challenge Europe.

For JOTA assistant team manager, Oscar Cooke, the levels of detail in the equipment he and the team use is critical and, in Sportscar racing in particular, jacking capabilities are amongst the most important.

'There's obviously different ways of lifting the car. If we need to do it within the pit stop, the car has an onboard air jacking system, which is factory fitted by ORECA using a combination of Stäubli and Krontec parts,' Cooke explains. 'If we have an air jack failure, we have pneumatic air bags that inflate to physically lever the car into the air to do the stop. Fortunately, we've never had to use this back-up facility, but they are there and ready if it is needed.

'In the garage, we use pneumatic high lifters, which is basically what you see when they lift the car within the garage on a simple plug-in airline method.'

Also available are compact aluminium trollies with custom mounting and support brackets, and bespoke bodywork stands.

Pneumatic, high-lifting jacks are usually constructed of aluminium and stainless steel and Greaves offers specially designed products with a billet machined base and support carriage, custom lift height, quick release brackets and optional splash adaptors.

Wheel guns

Dino Paoli Srl has been the trendsetter in wheel guns since it was founded in 1968. The Italian company's products are used almost universally across all top-end categories in motorsport and come in varying types.

As well as the guns themselves, Paoli also offer an extensive range of titanium, specialist steel and aeronautical aluminium sockets.

'They do everything to the guns that you need for use like an airline standard, the oil that goes into the gun and all the servicing kit,' says JOTA's Oscar Cooke.

'We run a model called the DP 5000 presently. We've looked at the Paoli DP 6000 product, which has a higher torque rating, and you can set the bias, too.'

The Paoli DP 5000 has a titanium motor, stainless steel trigger and a body made from magnesium alloy that means it weighs in at a comfortable 3.5kg.

The 6000 model has also taken another step with the so-called 'Hurricane' gun, which can exhaust air even quicker.

Essentially, the more air you can shift, the quicker it can spin up and achieve more torque. The 'Hurricane' consequently sounds a lot higher pitched as the rpm is achieved much quicker.

JOTA was testing this product ahead of the 2021 season on its specially created pit stop rig at its base in Kent, UK before it embarked on its WEC season with two ORECA LMP2 cars.

'We're finding different things we would change with the set up of the guns now,' says Cooke. 'Especially small adjustments to the angle of the handle towards the gun. If you imagine the body of the gun and the handle coming out at 90 degrees, this is quite awkward because it's built for an F1 stop where they're just going on and off one axle and are planted there on their knees.'

With a WEC pit stop, Cooke and his team must manoeuvre around a car more, moving from axle to axle, so what they're looking for from a wheel gun is quite different.

'We have modified it so we now have it tapered at 75 degrees, and that change of angle on the handle makes it much easier to move around the car.'

Then there is the trigger position. On the 'Hurricane', it is quite far down the handle, almost on the top of the hand, leaving a gap between the body and the index finger and thumb. 'That makes it more difficult to manoeuvre because you haven't got that grip and control,' details Cooke.

Consequently, some teams, including JOTA, have rapid prototyped and 3D printed their own extended trigger mechanisms so fingers can be kept even closer to the gun.

After some teams found an advantage in spending additional resources on optimising fuel stops, refuelling stations are now homologated in many formulae

That level of refinement to cater for the needs of the mechanics is required because, as Cooke explains, 'We find quite a lot that the people who design and build this stuff haven't actually done a pit stop themselves. They fire all their knowledge into it, but maybe practically isn't 100 per cent relevant.

'At the end of the day, these guns cost a lot of money [up to £12,000 a piece] and you've got to have two per car, so suddenly you've got £50k worth of guns.

'If the guys are uncomfortable using them, you shoot yourself in the foot, so the value of going that little bit extra and customising them is really worth it.'

John Rourke/AdrenalMedia.com

Refuelling kit

Endurance racing is a refuelling discipline, and so the technology and products used in the process are key to each team's strategy.

For LMP2 racing, Stäubli has a homologated refuelling system specifically designed for use on the ORECA chassis, which JOTA, and the vast majority of other entrants, use at the Le Mans 24 hour race.

The Stäubli (SAF) system has a nominal diameter of 45mm and a maximum allowable gravity pressure, as well as a safety connection design that prevents any fuel release until the socket is properly connected to the plug, at which point two levers must be pushed down and held.

The coaxial design enables safe and efficient refuelling during pit stops because it uses a single fuel and vent hose. Increased safety comes in the form of an FIA-approved dead man's switch, which has a lightweight design for ease of handling.

Once the connection between socket and plug has been made securely, the valve opens and allows fuel to flow until the operator releases the levers.

'With homologation and regs, there is a line length that has to be set, so that's from the bottom of the fuel tank on the fuel rig to the bottom of the nozzle,' explains Cooke.

Fuel cells and bladders are produced in a wide variety of ways by companies such as Aero Tec Laborotaries Ltd (ATL), all of which must meet, and indeed mostly exceed, the FIA standard FT3-1999, FT3.5-1999 or FT5-1999 certifications.

ATL has long been known as one of the leading design, development and suppliers to the motorsport industry and recently inked a six-year extension to its deal with TOCA and the British Touring Car Championship (BTCC) as sole supplier and technical partner.

ATL's new lightweight bladder, featuring the latest performance parts, will be used by every car on the BTCC grid up to and including the 2026 season.

These polymer designs meet FIA / FT3 and MVSS-301 specifications and, according to ATL, 'feature extremely low permeation rates.'

XPB

Drivers often become sweaty and communications can suffer over the course of a race, so even in-helmet microphones come under close scrutiny

XPB

Communications systems

Teams generally now use a wireless network system from the front of garages that connects to the 'prat-perch' and data is transmitted that way.

The engineers and strategists need to have good ergonomics on their stand and be able to spin 180 degrees to have full visuals for the pit lane.

It's all about creating an environment that is best for them to conduct and coordinate the racecars on track and, increasingly these days, communicate with engineers back at base or in virtual garages.

Some companies such as Greaves design bespoke engineer stations that include specific monitor layouts, while the likes of MRTC and Riedel Communications work with teams, broadcasters and promoters to bring audio visual equipment and remote production capabilities.

Complete pit carts can also be provided and are especially popular in US racing where NASCAR, IndyCar and IMSA teams often prefer to use two-tiered systems that are easy to transport and require minimal set up and breakdown time.

From a direct communications point of view, teams generally use both an intercom and radio systems. Intercom is for chat within the garage, with the engineers plugged in and usually in constant conversation throughout the race. Information is also transmitted through the intercom, which is all supplied by specialist motorsport communications company, MRTC.

The radio is only used for crucial messages between the car, driver and crew.

Some teams will go further, personalising their communication systems, looking for better, more reliable ways to deal with issues such as vibration in the car. Or more personal issues, as Cooke explains:

'One thing we've even looked at is the microphone inside the driver's helmet, and that's a huge step. We have 3D printed our own brackets that hold the microphone in a better position within the crash helmet.

'Drivers seem to create a lot of moisture from their mouths when they're speaking and so, after an hour or so in the car, it can sound like they've got their head in a bucket of water, so we're trying to find ways to waterproof the mic' and receiver.'

In Formula E, the main tool used in races is the race control notification system (RCNS), which is the primary means of communication between teams, the FIA, the race director and the timekeepers.

There are two basic means of communicating with the race director. One is through the intercom system, which is normally used by the race director during

» It's all about creating an environment that is best for [engineers] to conduct and coordinate the racecars on track

a race, the other is a direct line to team managers in the pit, which is the system provided by Magneti Marelli.

Set-up kit and tools

Away from all the hi-tech multimedia, a major part of racecar engineering is still set-up equipment, such as flat patches.

'JOTA's are all machined and engineered in house, specific to how we want them,' explains Cooke. 'That allows for geometry of the car, camber angles, tow angles, ride heights etc to be accurately measured.

Traditional hand tools still have a place in the pit garage too, of course.

Multiple Formula E champions, DS Techeetah, have an official partnership with Teng Tools, enabling the Franco-Chinese team to refine its hand tool requirements.

'We basically have a standard array in all our tool cabinets and each mechanic has a dedicated drawer, all of which are laid out the same,' says team manager and former Penske engineer, Nigel Beresford.

'But say we have a crash, and have to throw most of our resources onto the car that's damaged, it means borrowing mechanics from the other car.

'Even though they're on the other side of the garage, when they go to the drawer to get out, say, an 8mm spanner, they know it is in the same place as when they go to their own drawer. Everything is highly organised from that perspective.'

Remarkably, the Swiss-based Lista company is now offering drawer cabinets that can be individually equipped with integrated power modules.

'Thanks to the built-in socket in the drawer, mobile devices such as machine batteries, diagnostic devices, Smartphones or tablets can be stored safely and charged at the same time,' it states.

The human element

There's been a few big steps within multi-LMP2 race-winning Le Mans and WEC team, JOTA, over the years, but particularly intriguing is its work in the human performance aspect side of the company. Cooke explains:

'It's just everything down to where we've now found new technology that helps us study the way we do pit stops. A bit of an Anthony Davidson and his 'Sky pad' feel about things, if you will.'

'We've now found software we can load our own video into, and then pause it and study how we improve and develop the team.

'We also work with someone who has done a masters at university in body physics. She studies the way we do pit stops and works out how we can transfer the weight from our backs to our knees, and that's made a massive improvement.'

» Each mechanic has a dedicated drawer, all of which are laid out the same

Nigel Beresford, team manager at DS Techeetah

On the subject of massive improvements, simulation and strategy software is bringing major advantages in racing these days.

'We constantly look for ways to improve,' states Cooke, 'and the best way is to find it yourself, and not have to look at another team to see what they've done and copy them.

'If we find [an advantage] ourselves, it feels like a much bigger step.'

E safety

Safety equipment and clothing is a standard part of any motorsport team's kit but, with the advent of all-electric racing – starting with the FIA Formula E championship in 2014 – a whole series of new procedures had to came to the fore.

As racecar batteries become more powerful, so safety protocols around handling them become more important than ever

John Rourke/AdrenalMedia.com

Each Formula E team member that works on the cars now must go through a mandatory safety course before they attend an official event, because the technology involves extremely high-voltage (HV) systems and lithium-ion batteries that bring with them different electrical, chemical and fire risks that have to be carefully managed.

As the championship grew in popularity, the FIA conducted thorough analysis of potential situations and developed specific training procedures to ensure a high level of operational safety.

'I think our team's in the vanguard on that side of things,' says DS Techeetah's Nigel Beresford. 'We've bought our team members specially commissioned, long, insulating aprons to fully shield their bodies from shoulder to ankle when they're connecting and disconnecting the battery.'

Most non-car specific tasks are now given over to a chief electrical specialist, who assumes technical and supervisory roles for all issues regarding e-safety during a Formula E event. They will be in direct contact with the staff (volunteers and officials) at the track and, if required, support the race director's decisions. Their responsibilities include performing the role of functional manager for the electrical FIA team and all HV roles, determining where standard operating procedures should be displayed in different workspaces and monitoring and enforcing compliance with the FIA and electrical regulations.

» We work with someone who has done a masters at university in body physics… and that's made a massive improvement

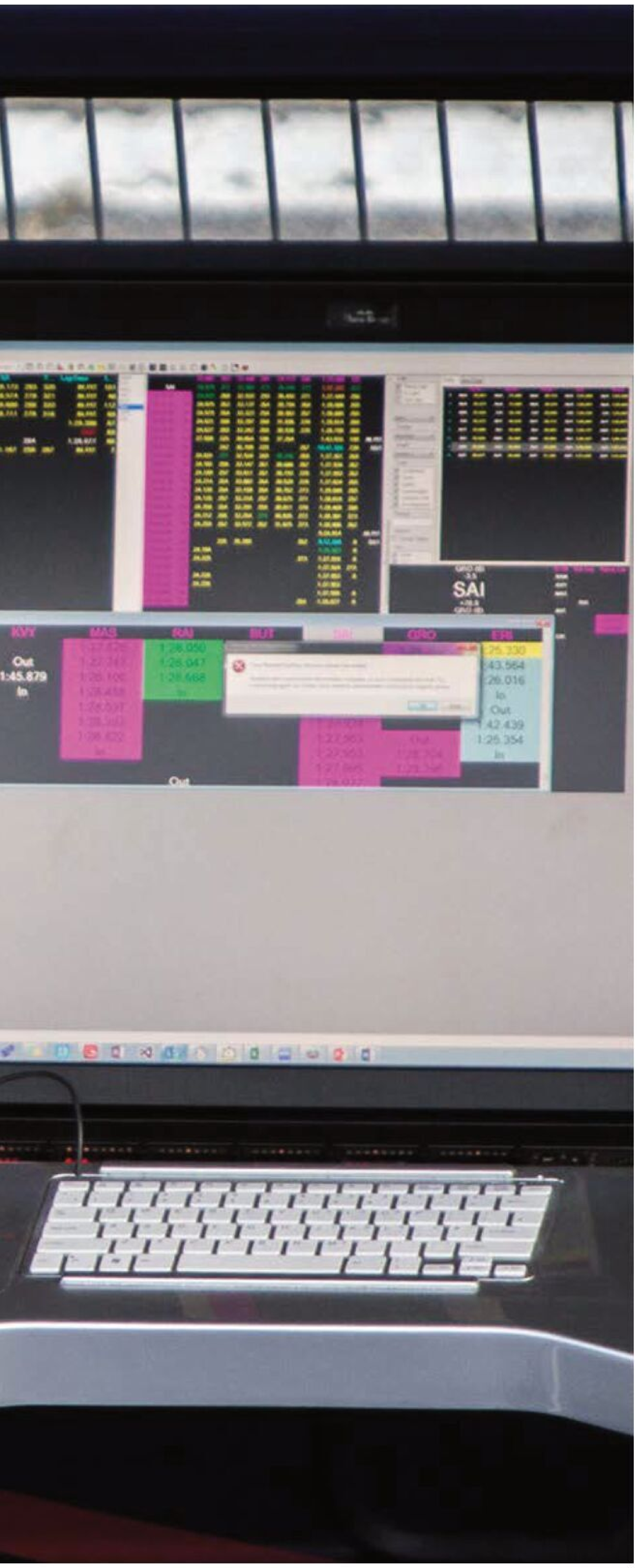
Oscar Cooke, assistant team manager at Jota

It's all a far cry from the days when mechanics carried their own tool boxes, fuel was sloshed around like water and team's entourages would hang out in the pits during a race drinking and smoking cigarettes… ●

The virtual garage

Racecar investigates the latest advances in the ultra hi-tech data and communications systems in Formula 1

By LAWRENCE BUTCHER



Formula 1 runs on data, and every element of each team's operation is monitored and analysed to the n'th degree. The reason outfits such as Mercedes are so successful is because, among other factors, they have the best grasp of the data available to them and are able to process and understand it rapidly.

This is only possible thanks to a constantly evolving array of tools used to record, store, transmit and analyse that data. And, most importantly of all, filter out that which is most significant. The ideal situation is for every department to access whichever data it needs, at any time, and interrogate it to achieve a competitive advantage.

This data-driven approach to racing has seen the pit wall steadily extended. It now encompasses the garage, paddock and the factory the racecars are built in, creating a virtual garage environment where dedicated teams of engineers can analyse car performance and race strategy away from the high-pressure atmosphere of the track.

To achieve seamless data flow across the globe, teams need an IT and communications system that is both efficient and resilient, and it should come as no surprise that many teams' current sponsorship deals with relevant technology companies go hand in hand with technical partnerships.

Moving data

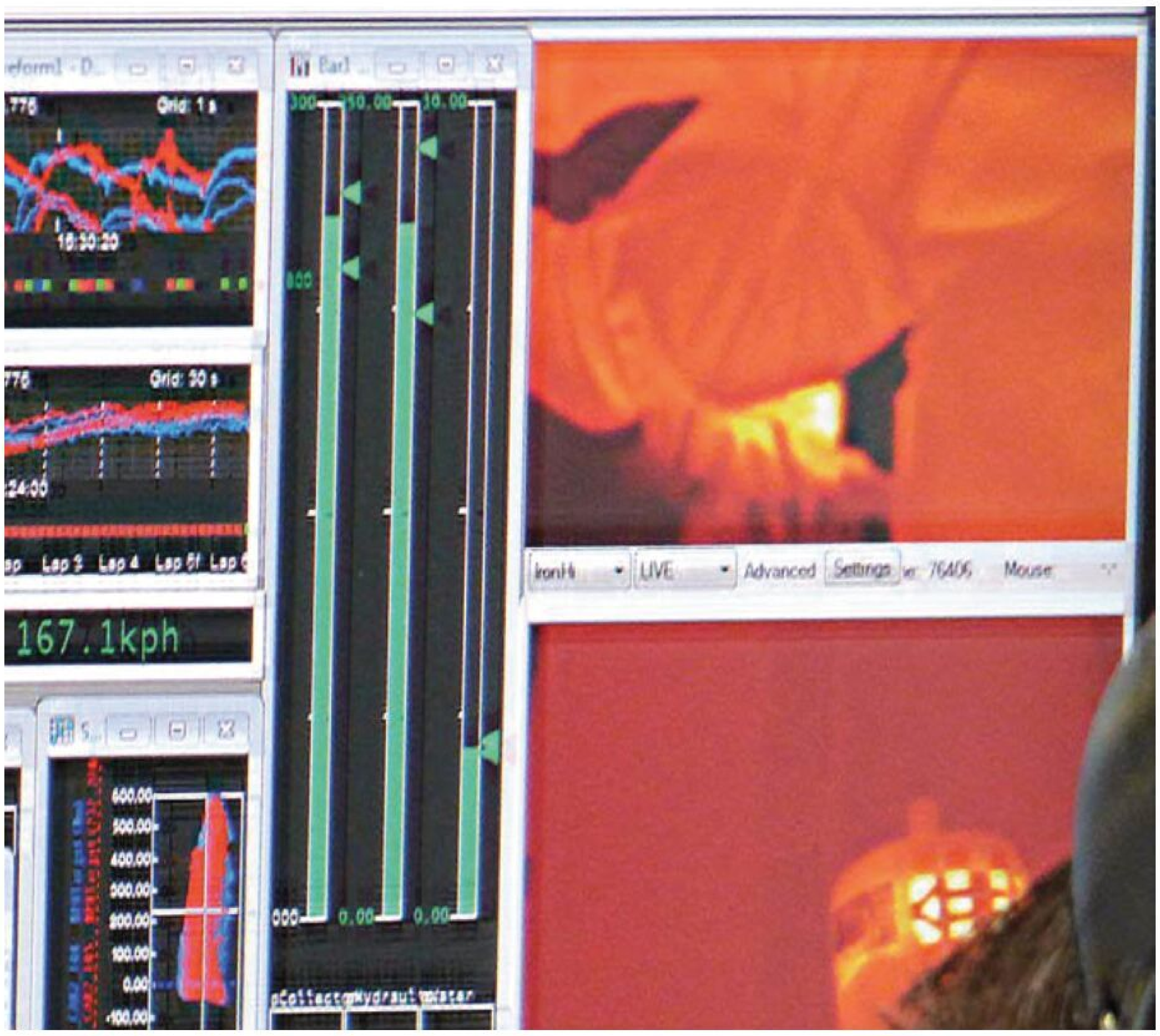
With approximately 300 sensors installed on a car during a race weekend collecting gigabytes of data, simply moving the information harvested through practice, qualifying and race sessions is an onerous task. It needs to be moved quickly, so that both real-time and offline simulations can be conducted to refine set-ups, strategy calls calculated and preventative maintenance issues dealt with in good time.

Whereas a decade ago, most sensors only recorded parameters such as position, speed, load and temperature, in recent years the use of video-based data collection has increased exponentially. For example, thermal cameras, in addition to infrared thermal sensors, are used to record tyre data, while other cameras can be deployed across the vehicle and in the pit lane for pit stop and performance analysis. And teams are not only looking at their own cars, but also the competition, trying to work out their strengths and weaknesses.

Core operating data from the car will be transmitted via the telemetry system to the pits over the course of a lap, though the bandwidth of this is relatively narrow and so is limited to important readings related to powertrain and chassis performance. More detailed data will be downloaded when the car comes into pit, traditionally through a hard cable connection, though some teams have deployed sophisticated systems to dump data either each lap, or before the car enters the garage after a stint.

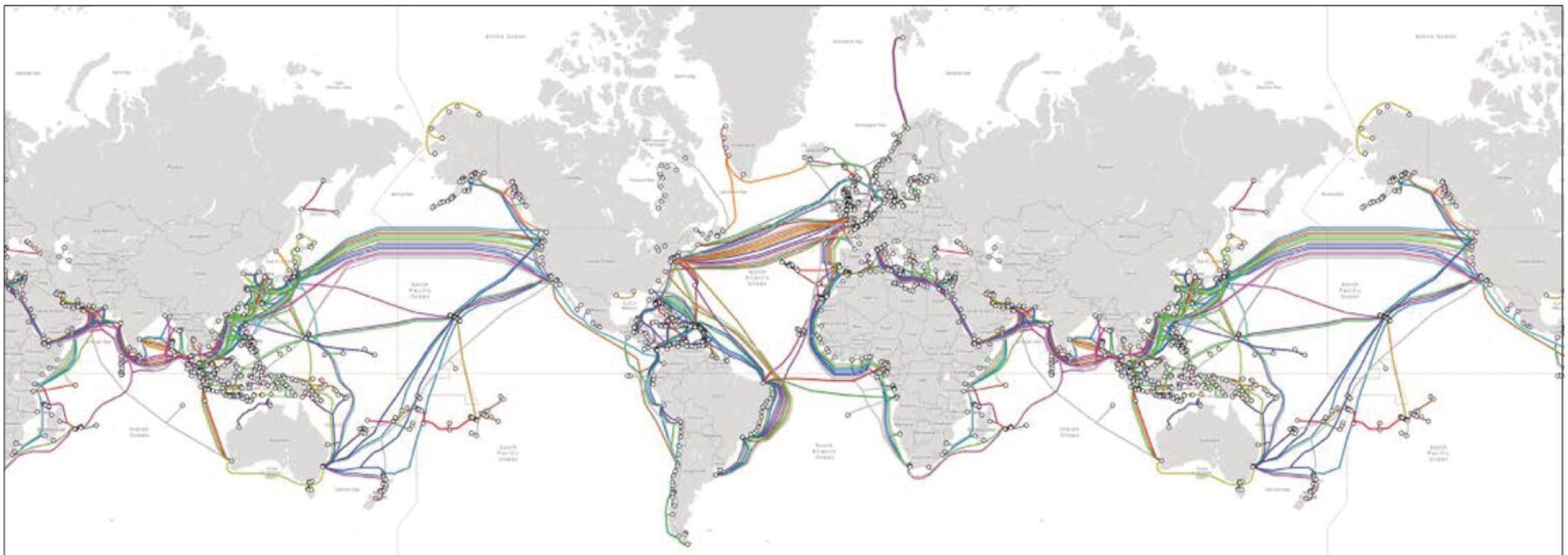
For example, since 2017, working with technology partner Qualcomm, the Mercedes Formula 1 team has been using a high-speed Wi-Fi system located at the pit entry to dump thermal camera data from its cars as they pass by, making it available to engineers to analyse before the car even enters the garage.

» The ideal situation is for every department to access whichever data it needs, at any time, and interrogate it to achieve a competitive advantage



Downloading thermal data can help powertrain engineers monitor how a car is running before it pits

Red Bull AT&T operations room



Fibre optic connections are not limited to land, this map shows some of the under-sea network that links the globe. F1 partner, Tata Communications, owns over 500,000kms of sub-sea network

At the time of its introduction, the system relied on a 60GHz, 802.11ad Wi-Fi connection, albeit highly uprated by Qualcomm, capable of data transfer at a rate of 200-600Mbit/s, about three times faster than a standard 802.11ac system. Since then, the team and partner have been working on moving other data beyond tyres, and also transmitting each time the car passes the pits, while also investigating 5G-based C-V2X (Cellular Vehicle to Infrastructure) transmission, but so far remain tight lipped about the results.

Hard networks

Once the data is grabbed from the car, it then needs to be distributed around the garage and paddock and on to teams' facilities back at their factories, in addition to F1 and the FIA's race control networks. On a race weekend, a team's IT staff will install a high-speed ethernet connection between the pit wall, garage and paddock, providing a real-time connection across all elements of their operation. The use of a hard network is vital for two reasons: first, Wi-Fi is too susceptible to disruption in the 'noisy' environment of a pit lane and second, wired connections are far more secure, reducing the chance of another team pilfering critical data.

From the track, teams need a secure and very high-speed data link back to their bases, in order to fully utilise the 'Mission Control' concept, allowing engineers at the factory to augment those at the track in real time. This connection will be provided by a third-party supplier and invariably use fibre optic links capable of data transmission speed in excess of 100Mbit/s. On top of this, there can also be back-up systems relying on satellite and cellular connections.

Fibre optic cable networks span the globe (there is even a fibre link between the islands of French Polynesia), and are capable of providing low latency, high speed data flow. Technical partners come in very useful here, as setting up a dedicated connection from a new location every week is far from cheap.

Tata Communications, for example, which until 2020 was heavily invested in F1 as an official partner and of several teams, owns over 500,000km of sub-sea and 210,000km of terrestrial fibre cable network. This means it can provide customers with dedicated fibre links, even in remote corners of the globe.

In the case of Red Bull, partner AT&T, handles its communications needs and has staff trackside at every race to set up and break down the required infrastructure, even going so far as to lay cables to local exchanges from the garage if necessary.

» **Technical partners come in very useful here, as setting up a dedicated connection from a new location every week is far from cheap**

In the Mercedes factory, HPE Moonshot bladed CPUs are used in their thousands for CFD simulation work

The technical detail of these network set-ups is beyond the scope of this article, but there are a number of different approaches to creating a resilient international link. Traditionally, if you wanted to establish a reliable data connection between two remote locations, the go-to solution would be an MPLS (Multi-Protocol Label Switching). MPLS is a routing technique for telecommunications networks that directs data from one node to the next based on short path labels rather than long network addresses. This avoids complex lookups in a routing table, which can restrict traffic flow. MPLS's main advantage is that a very reliable (in data terms) link can be created. However, when it comes to high demand for bandwidth, it can be very costly, and also potentially vulnerable to data breaches.

For these reasons, some teams have started to utilise SD-WANs (Software Defined Wide Area Networks). These virtualise network functions so they can run as software on commodity hardware, whereas MPLS technology must run on proprietary hardware. SD-WAN connections can also utilise dedicated lines or public networks, while MPLS can only use the former.

In certain cases, an SD-WAN can also integrate MPLS as one of the SD-WAN connections. McLaren is one team that leverages an SD-WAN via its partner, NTT Communications, the Woking, UK-based outfit having moved to the system in 2018 to help it better handle the bandwidth-hungry video data it was harvesting at races.

Crunching the data

The computational power needed to process the reams of data gathered over a weekend is considerable, and the F1 pit lane is a great display of edge computing. This term refers to putting computation and data storage at the edge of a network where data is gathered, so it can be used for tasks such as simulation and data analysis, without having to rely on centralised HPC (high performance computing) resources. This is not to say teams do not make use of their factory data centres as well as cloud computing facilities, but having considerable computing firepower trackside is vital when making split second strategy decisions.

To this end, every team has a data centre in its support trucks. The power of these has increased considerably in recent years, even as their physical size has decreased. Not only has this broadened the range of tasks that can be undertaken at the track, but also, somewhat surprisingly, reduced costs. For example, when Williams updated its trackside servers, it was able to move from four-rack units to two, which reduced the overall weight of the system. With air freight coming in at $300/kg, the savings on shipping the kit from round to round meant the upgrade paid for itself in nine months.

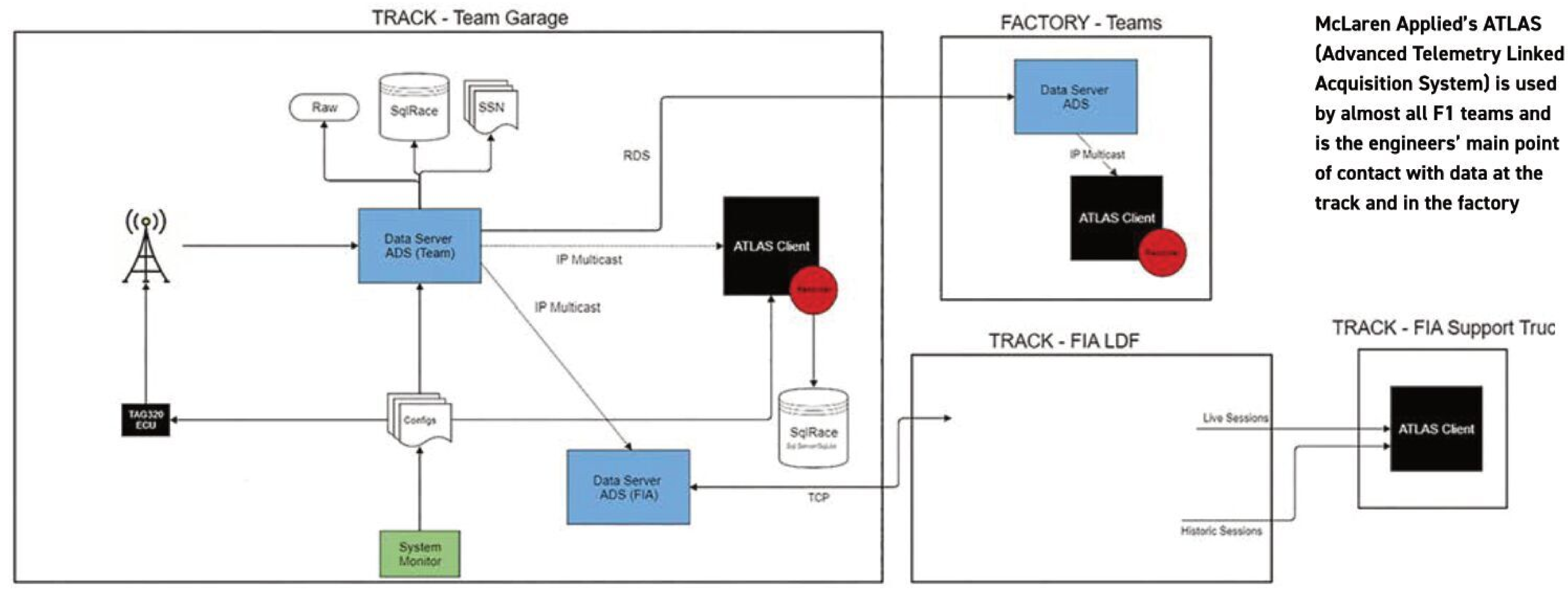
Williams also found greater performance. The increasingly large data sets produced by the car's telemetry system, plus the proliferation of high-definition video, meant that the input / output of storage was causing bottlenecks in the transfer of information around the team. It could take the trackside engineers up to three minutes to open up a data set for analysis, which is an age in the short gaps between track sessions.

The team consolidated its computer resources and storage into a single chassis (the racks of computers one sees in a server room). The resulting system allowed more efficient assigning of resources to various tasks and faster processing of those tasks, thanks to the storage being on board each chassis, rather than relying on a centralised network storage system. According to the team, this gained up to 11 times the throughput it had been getting from its network-attached storage. The real-world impact of this improvement meant engineers could access full data sets from the car in around six seconds, rather than the two to three minutes it had previously taken.

In the case of Mercedes, which has a technical partnership with Hewlett Packard Enterprise, it uses the company's latest HPC kit trackside. In its factory, the team relies on HPE's Moonshot, a converged, bladed (where CPUs are mounted on blades that slot into racks) HPC system, originally developed for the financial services industry and renowned for its high performance and energy efficiency. It uses several thousand of these processors for its CFD simulation work.

In 2019, it moved the same technology to the edge, consolidating its trackside infrastructure of 16 units into a single, rugged HPE Edgeline 4000 chassis, designed for edge applications. The simplified system had greater resilience and performance, allowing for faster data crunching during the crucial seconds of qualifying sessions.

Mercedes F1's technical partnership with Hewlett Packard sees it use the company's Edgeline 4000 chassis for high speed trackside data crunching



McLaren Applied's ATLAS (Advanced Telemetry Linked Acquisition System) is used by almost all F1 teams and is the engineers' main point of contact with data at the track and in the factory

Mercedes also takes full advantage of is its partnership with specialist Pure Storage, which has supplied solid-state flash storage across all of the team's infrastructure. As anyone who has switched from a traditional HDD to a flash drive will know, these are far faster and, for Mercedes, the shift saw a cut in response times for key database queries of 95 per cent. Similarly, the time needed to open data files reduced by two thirds and it saw a near 70 per cent reduction in the space occupied by its data centre racks.

In this Internet of Everything age, teams are not limited to the computing power they physically possess, and many now also turn to cloud resources for rapid scaling to meet complex computational tasks. Big players such as Amazon Web Services (AWS) and Microsoft feature prominently, alongside others such as Aston Martin Racing's tie up with Cognizant and Red Bull's with Oracle. The most evident to the viewing public is, of course, F1's deal with AWS, which is used to generate in-race insights, and was deployed for development of the 2022 regulations.

These partnerships do not just bring access to computing power in the cloud, but also expertise in areas such as machine learning and data management. For example, Ferrari has recently signed an agreement with AWS and will use its Elastic Compute Cloud (Amazon EC2) system, and is set to build a data lake with Amazon Simple Storage Service (Amazon S3) and AWS Lake Formation to gather, catalogue and clean petabytes of data. Having all of this data centralised allow it to 'scrape' for patterns that might affect car performance.

Data sorting

It is one thing being able to move data around the globe in real time, but it's what teams do with it that counts. It has to be sifted and relevant portions dished out to those that need it, while being presented in such a way that engineers can quickly see important changes or trends.

Almost universal across the grid when it comes to monitoring car operating parameters is McLaren Applied's ATLAS (Advanced Telemetry Linked Acquisition System). Glance at any garage on a race weekend and various ATLAS displays will be apparent, each team having its own data workbooks incorporating various displays and pages. The system is most engineer's main point of contact with vehicle data, and is used both trackside and at the factory.

It should come as little surprise that, as one of the originators of the mission control systems that are now commonplace, McLaren Applied ensured global networking capabilities are incorporated into ATLAS. The Atlas Data Server (ADS) features a Remote Data Server (RDS) function allowing the daisy chaining of two or more ADS, and simultaneous broadcasting to two ADS for multicasting to other network clients.

However, there are many other systems teams use to interpret their myriad data streams. Pit stops, safety cars – both physical and virtual – as well as the actions of the other teams all dictate the split-second tactical calls teams make, and many have developed tools to aid in this. For example, UK-based SBG Sports Software, which specialises in performance analysis software, has worked with Mercedes since the last days of Brawn, refining its Race Strategy software system to provide up-to-the-second analysis of these tactical situations, incorporating the video feeds from the various cameras recording the race.

Via a series of customisable worksheets, engineers can quickly access and overlay the data they need to make decisions from the pit wall, including not only that provided by the FIA, such as GPS and sector times, but also inputs from a team's sources, predicting tyre degradation, pit stop windows and the like.

» In this Internet of Everything age, teams are not limited to the computing power they physically possess

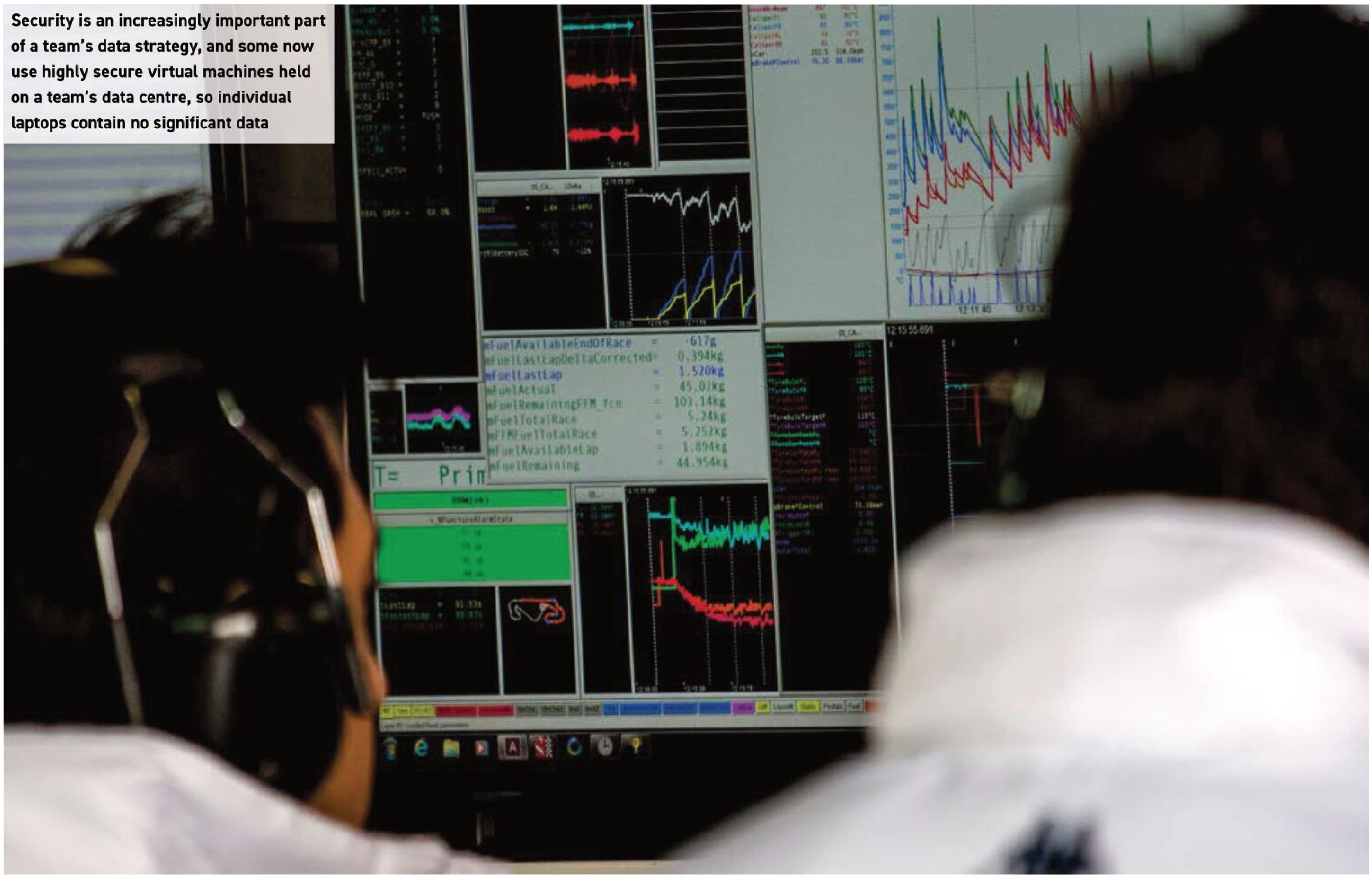
As well as making in-race calls, the system can also be used for pre- and post-race planning. The team will feed data into the system and run through a multitude of scenarios to work out the impact of various events on its tactical calls, even going so far as to run full race simulations with engineers operating in real time. Similarly, it will also use the system for post-race analysis and debriefing, with every channel of video, radio data and relevant telemetry recorded.

Trend spotting

It is not just race strategy where teams such as Mercedes have benefited from having well-developed tools. Given the huge amount of data produced by the team's modelling and simulation programs, spotting trends that highlight fruitful development directions can be challenging.

The Brackley, UK-based team deploys a data analytics suite from technical partner, Tibco, called Spotfire. This allows it to review and amalgamate various data streams for visualisation, making it easier to spot trends over time periods from a single race session to an entire season. By being able to identify automatically what is 'normal' in data sets, analysts can better focus their efforts on investigating areas that may be of concern, filtering out the 'noise' of regular data.

One of the first applications for Tibco's technology was the development of improved gearbox control systems, and



Security is an increasingly important part of a team's data strategy, and some now use highly secure virtual machines held on a team's data centre, so individual laptops contain no significant data

finding new avenues for development of the power unit. In the past, teams such as Mercedes would use relatively crude methods such as Excel spreadsheets for this type of analysis. Mercedes is, of course, not the only team exploiting the latest advances in data analytics and management from outside sources. Nearly every team has at least one technical partner that specialises in data analysis or other IT-dependent activities.

Data security

In just the same way that everyone now takes steps to prevent some ne'er-do-well pilfering their personal information online and taking out a mortgage on a house in Majorca, F1 teams must also take data security seriously. Teams are regularly subject to hacking attempts, ranging from regular malware attacks through to extreme ransomware cases. Again, many teams turn to technical partners to implement a multi-layered approach to security, covering both day-to-day IT operations and the more F1-specific cases such as sensitive data transfer from car to pits to factory.

Looking again to Williams, which has a long-standing partnership with data security and management specialist Acronis, it works on the principle of protecting its data, rather than necessarily ensuring every laptop and desktop computer is 'secure'. This is achieved by team members accessing virtual machines, which reside on the team's data centre and are protected by many layers of security. This means individual machines do not actually contain any data, it all stays within the network and Acronis' Cyber Protect package monitors usage to automatically flag any unusual behaviour.

The same system also ensures that data is always backed up, removing the onus from the individual team member. Implementing such a system is no small task. In the case of Williams, its IT system incorporates approximately 600 individual servers, 1500 workstations (known as end points) and some 1200 email inboxes, with around 0.5 petabytes of data.

Williams has it relatively easy in that its engineers are either at the track *or* the factory. For a team such as Haas, which has bases in the UK, United States and staff in Italy, the data security problem is even more complex. One tool the American team uses to mitigate threats is the Nominet DNS platform, which monitors Domain Name System traffic to automatically detect threats, be they malware, phishing or data theft. Thanks to the automated process, the team says it is able to achieve far greater coverage than human IT operators could and react faster.

Of course, no system is entirely foolproof, and it is still possible for a 'trusted insider' – someone within a team who might be leaving to work for a competitor, for example – to walk off with valuable intellectual property (IP) on a flash drive. Or, in the case of Williams, for the back end of its marketing-led, augmented reality app to be easily accessed, releasing accurate 3D models of its current car out into the wild.

» The IT and communications specialists are the unsung heroes of modern F1 teams, managing phenomenally capable systems that push the boundaries of modern connectivity

However, with the increasing sophistication of automated data security systems, such incidences are far more likely to be flagged up and nipped in the bud before any real damage is done.

Overall, it is fair to say the IT and communications specialists are the unsung heroes of contemporary F1 teams, managing phenomenally capable systems that push the boundaries of modern connectivity in order to gain that elusive competitive edge. ●

Networking

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

By STEWART MITCHELL

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

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

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

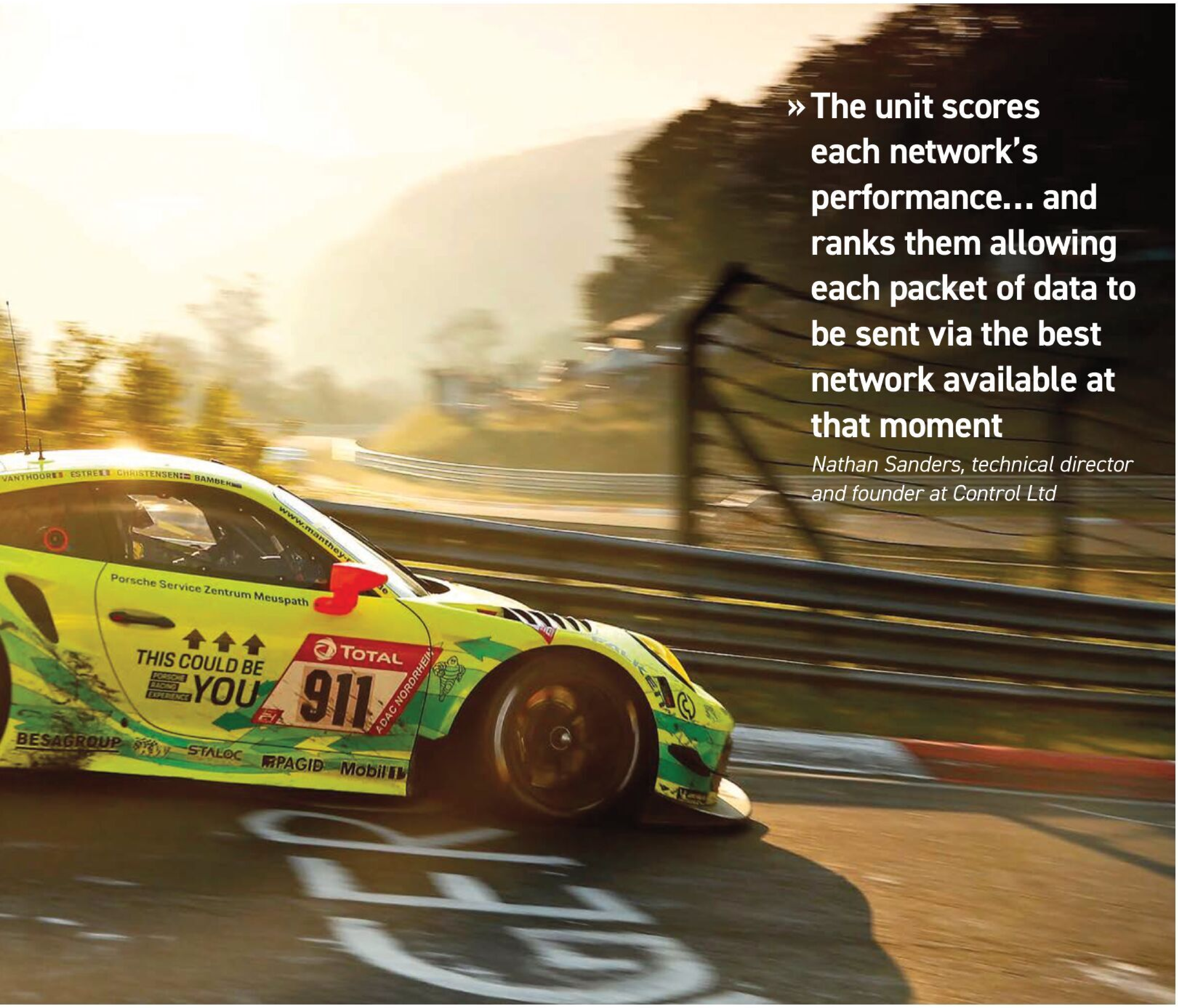
The challenges of coverage are a function of the distance over which radio transmitters can transfer signals and data. Radio doesn't go very far and causes major signal issues at large circuits, especially those with significant gradient changes such as the Nürburgring or Spa Francorchamps.

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

Porsche

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

Control Ltd



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

Nathan Sanders, technical director and founder at Control Ltd

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

XPB Images

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

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

Cellular modems

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

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

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

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

Multi-modem systems

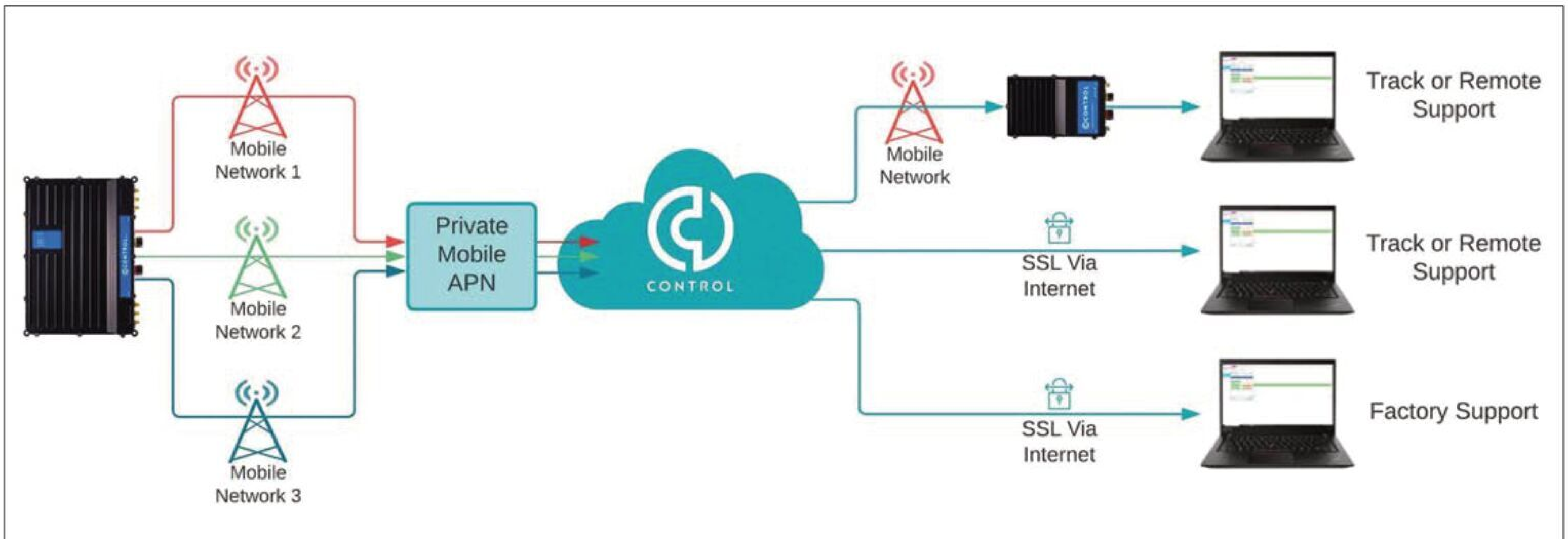
In the last few years, cellular data transmitting systems have evolved to combat this in the form of multi-modem units. Basic cellular data systems use an industrial modem designed to send serial data between one machine and another, but the latest motorsport telemetry transmitting systems feature bespoke PCBs and a complete software stack specifically designed for the application, which enable it to use multiple SIM cards to connect to numerous networks at once.

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

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

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

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



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

Control Ltd

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

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

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

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

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

Data management

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

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

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

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

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

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

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

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

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

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

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

'These systems allow teams to arrive at set-up optimisation earlier, and the time engineers can save could

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

Porsche

amount to huge savings in track time, days in the season's testing schedule and tens of thousands of pounds.'

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

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

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

Race strategy

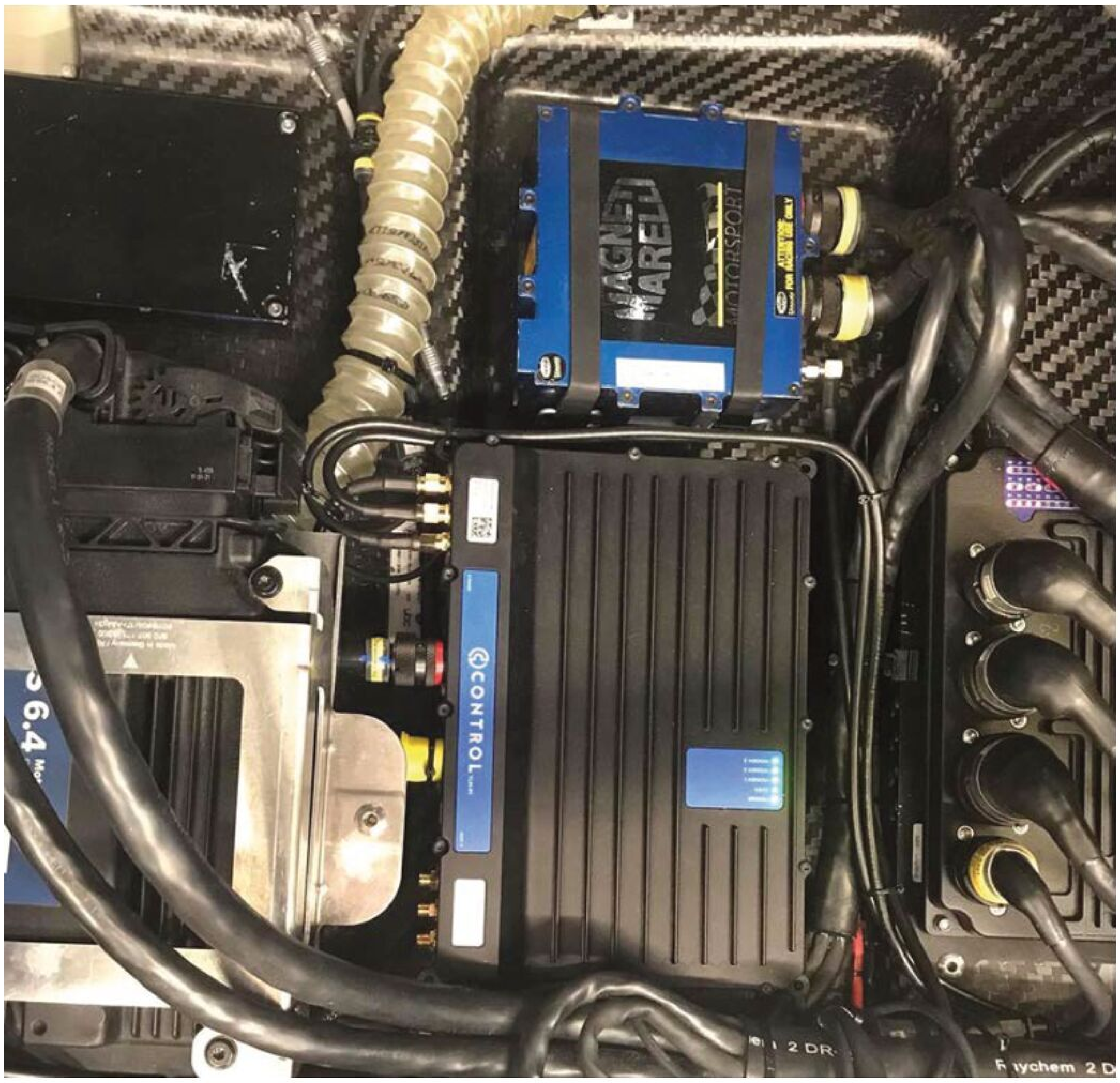
Today's upper echelons of motorsport, such as Formula 1 and Le Mans Prototype racing, feature regulations that are forcing contenders to become increasingly more efficient, and without live, reliable data, teams can be at a fairly significant disadvantages in terms of race strategy. Things such as understanding the car's fuel burn can make a difference, especially in changeable conditions such as slow zones, safety cars and changeable weather conditions.

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

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

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

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



Control Ltd

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

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

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

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

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

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

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

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

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

'Doing predictive analysis on when your competitors will stop, understanding traffic management and how the car's potential and behaviour changes as the fuel load drops and the tyres degrade are primary inputs into race strategy,' says Sanders.

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

Safety considerations

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

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

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

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

Machine learning and AI

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

'Our modems send up information every two minutes to our cloud platform about what percentage coverage they've got, what their signal strengths are and what network they're on,' explains Sanders.

'We can work out the race track they're at based on the cell towers they can see. We put all of that into a machine learning model, and it works out the best network, or combination of networks, for a given racetrack. It also carries out diagnostics like antenna anomaly detection.

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

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

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

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

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

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

Nathan Sanders, technical director and founder at Control Ltd

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

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

AI is currently extensively exploited in simulation, testing and developing race strategy before a race using previously collected data and increasingly is being used in other forms of the sport, even reaching customer racing. It's safe to say, then, that AI has its place in motorsport, and it's all based on reliable telemetry transmission. ●

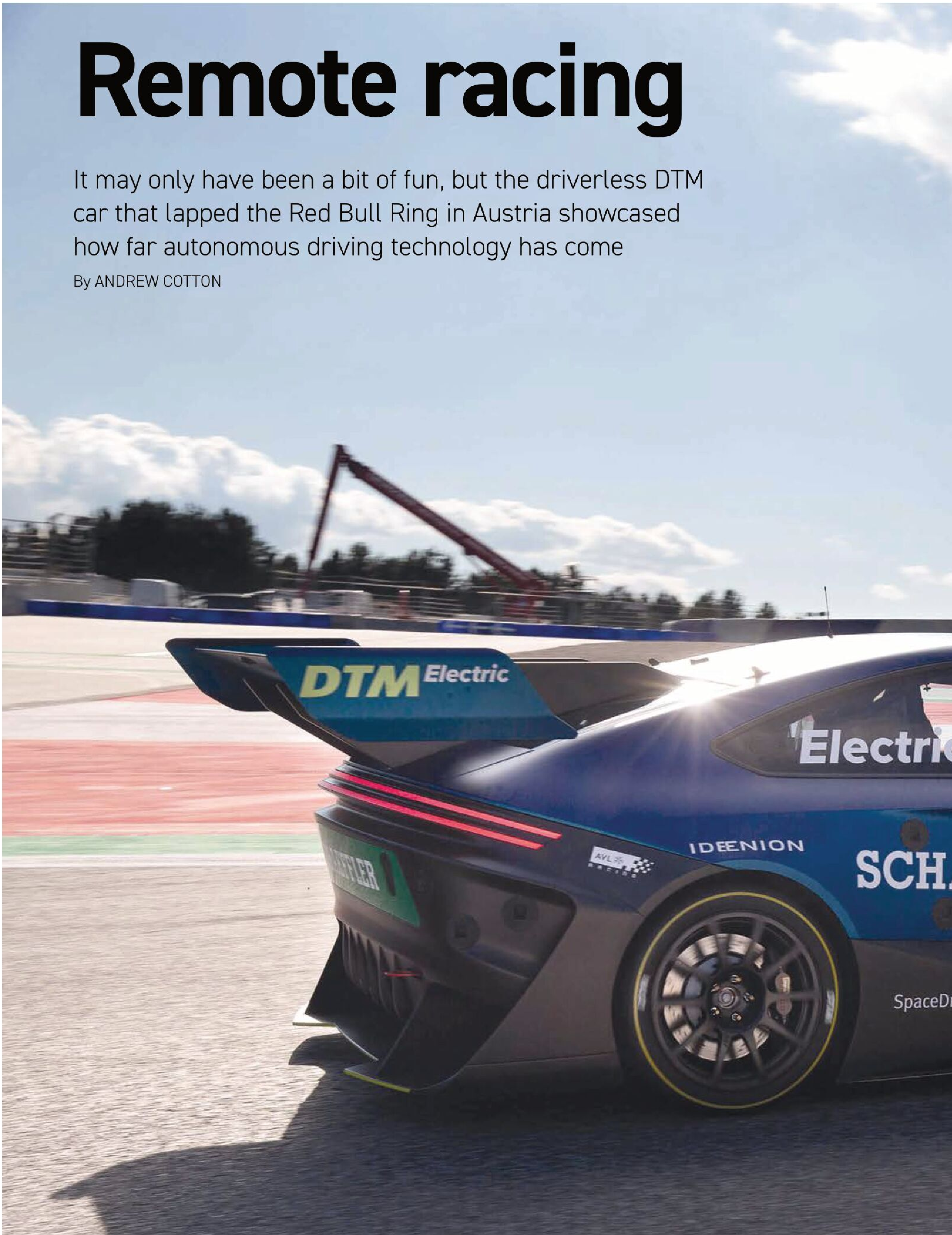
Like all the other electronics in modern-day motorsport, telemetry systems must be robust to withstand all racing and environmental conditions, including occassional airborne moments

XPB Images

Remote racing

It may only have been a bit of fun, but the driverless DTM car that lapped the Red Bull Ring in Austria showcased how far autonomous driving technology has come

By ANDREW COTTON



Ellen Lohr, director of motorsport at AVL, whose vehicle dynamics simulation software, VSM RACE, helped make the extraordinary demonstration possible

» **Software behind the simulator is absolutely state-of-the-art and differentiates us from our competitors**

Ellen Lohr, director of motorsport at AVL

History was made at the DTM race in Austria at the start of September, 2021, as the all-new electric car that will form the basis of the future DTM rule set lapped the Red Bull Ring at full racing speed. Not only did it complete a lap of the Spielburg circuit in the hands of former champion driver Rene Rast, but another driver, Tim Heinemann, also took the car around the Austrian track from behind the wheel of the AVL simulator, more than 80km away.

The latter was an extraordinary achievement, marrying some established technologies to create a unique occasion. Using the communications from Riedel, the 5G network from Cisco for network communication and AVL's hardware-in-the-loop simulator, the combination allowed Heinemann to complete the lap with speeds of up to 150km/h.

There is nothing new in terms of bringing together hardware-in-the-loop technologies, but sending a 1200bhp, full-size racecar around a circuit without a driver on board in order to demonstrate it to a live audience took some courage. However, it was the next step in the development of the DTM Electric concept, that was announced in 2019, and which matured into a full demonstration racecar a year later.

Remote Run

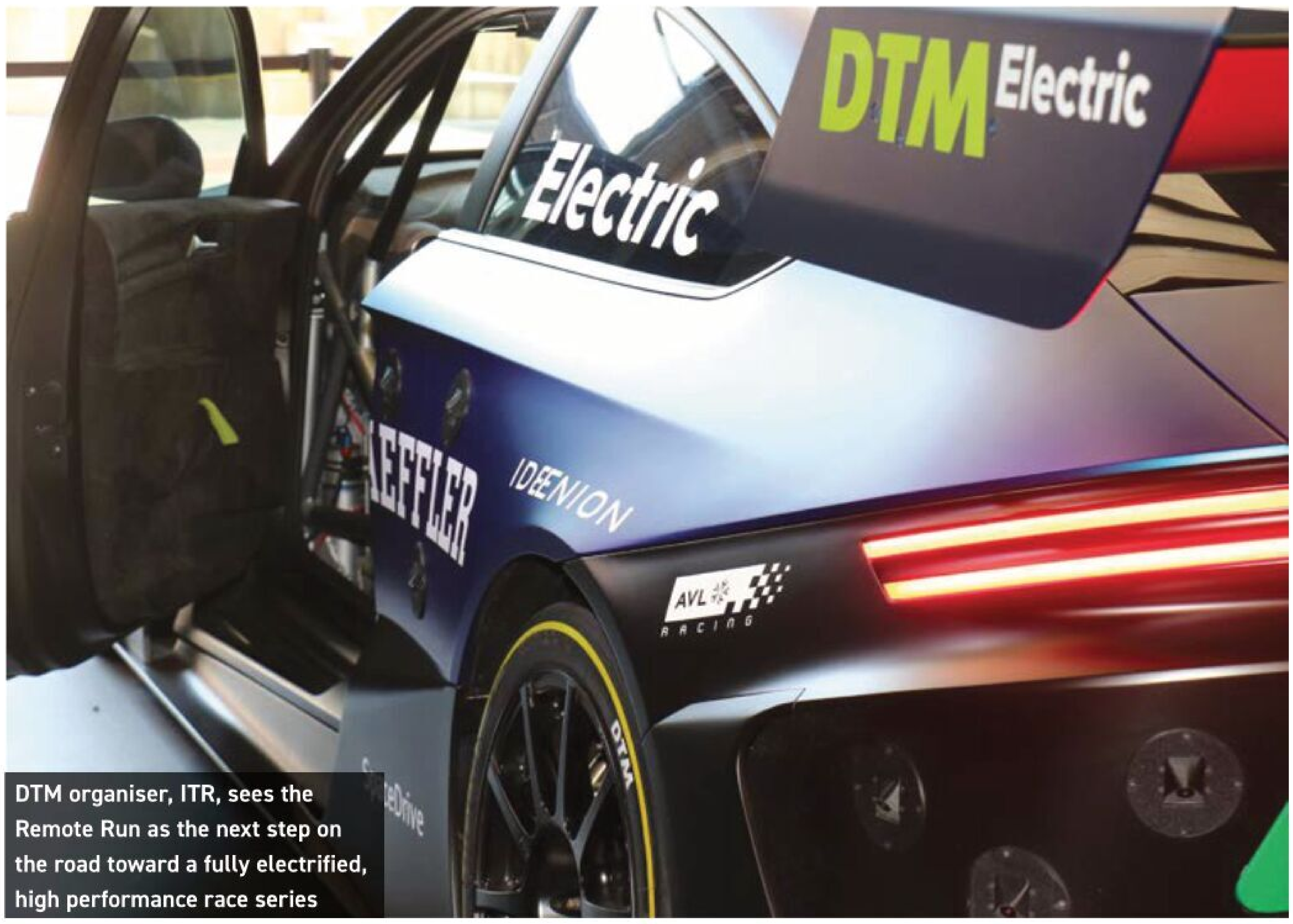
'The DTM Electric Remote Run is the next step on the way towards a fully electrified high performance race series,' says Benedikt Bohme, managing director of the DTM organisation ITR. 'The project is showing elements that in the future could be used in a fully new, global, electrifying race series like we want to establish with DTM Electric, alongside the proven DTM.

'Moreover, it shows the innovation power our platform has for developments aimed at mobility in the future.'

Of course, having an electric car is not critical to making a vehicle autonomous. There is every opportunity to make an internal combustion engine car autonomous as well but, in order to lap the track with a driver in another postcode, the high level of electrical systems onboard were key to making the project work.

These electrical systems included Schaeffler's Space Drive system, which has been tested in race conditions for a number of years. The steer-by-wire system removes the steering column from the process, so the signal is simply transmitted to the simulator, rather than the steering wheel.

However the complexities of driving the car around a track include avoiding latency in the signal, which could cause the driver to miss a braking point, for example, and travelling at full speed that could lead to a sizeable accident. For that, there was a kill switch for the physical car that would have applied the brakes immediately and fully, while there was also a kill switch in the simulator in case of blue screen for the driver. To bring all these technologies together, and have them function to the point where a car could be driven at speed, took great coordination. Other companies such as Tripleye provided the connected camera system, including the all-important computer unit, and Vosys supplied the software, its integration for tele-operated driving. Memotec, a proven sensor partner of the current DTM platform, was also involved, ensuring communication between car and simulator was clear.



DTM organiser, ITR, sees the Remote Run as the next step on the road toward a fully electrified, high performance race series

Farid Wagner

» It shows the innovation power our platform has for developments aimed at mobility in the future

Predictive behaviour

Key to making the virtually-controlled lap happen was AVL's vehicle dynamics simulation software, called AVL VSM RACE, which can be used in offline simulations, in the cloud or in real-time applications such as driving simulators, and vehicle and battery test benches. The software accurately

The car on AVL's Full Vehicle Dyno, capable of generating the 800kW needed for Formula 1 and modern EV racecars

simulates vehicle behaviour and enables improvement of all vehicle systems from the concept to the testing phase.

'We do not actually have the most expensive driving simulator,' admits AVL's director of motorsport, Ellen Lohr. 'Top motorsport teams may have more expensive ones, but our software behind the simulator is absolutely state-of-the-art and differentiates us from our competitors.

'We can do everything from modelling tyres, different concepts of cars, and we can run hundreds of thousands of laps in simulation with a click of the mouse. We have several features that make our software stand out from the rest. One that we are particularly proud of is the real time connection between the driving simulator and the actual car, which is at the same time being run on our Full Vehicle Dyno. In this case, you have the driving simulator and the actual car in completely separate buildings.'

There is a different challenge to driving a genuine car that goes around the track at close to full racing speed compared to driving a simulator. The first thing that had to be addressed was safety, and in this case the primary concern was latency in the system. If the latency in the system was too high and there was significant delay between the physical car and the input from the system to the driver in the simulator, the driver would have less control of the car if it went sideways, for example, and there would be a higher risk of accident. Even having a missed braking point could have had at best embarrassing consequences, at worst a crashed car.

Practice runs

'Undoubtedly, having a low latency was crucial to be able to drive the car at high speed,' confirms Ull Thaler, senior software engineer, racing at AVL. 'Before we attempted remote runs with the real car, we used the simulator with a modified VSM model where we added artificial latency in order to test the effects on driveability in a controlled setting. We found that a round-trip latency of 150ms is the maximum where the driver still felt they had a good positional control over the car, that they could hit the apex reliably.'

This may sound like a lot, particularly when Vosys, which provided the network over which the DTM car was able to communicate with the simulator, has a quoted latency of 60ms over a 4G network that it uses in its association with companies such as Volvo trucks, but actually it isn't. Even with the smart video packaging that makes sure only video crucial to the operator or driver at any given moment is available, which minimises the area sent over the video link, latency was still a concern for AVL.

'This latency number [of 150ms] refers to the sum of all elements of the system including cameras, network links, actuators in the car, data transfer back and forth, sensors, processing time, projector response time and so on,' says Thaler. 'When you put all of these elements together, it does not leave a lot of margin for the individual subsystems.'

» A round-trip latency of 150ms is the maximum where the driver still felt they had a good positional control over the car

Ull Thaler, senior software engineer, racing at AVL

Cumulative latency

Having fixed the latency number and put in safeguards around any peak that was above what AVL considered acceptable, the next question of cumulative latency arose. Would the latency continue to accrue as the car completed a greater distance?

'The latency does not increase with running time, only when the car switched between the network nodes that were placed around the track,' explains Thaler. 'The latency would increase for an instant, but overall we stayed well below our established limits.' Redundant links and super fast congestion

Before the Remote Run took place, simulations were conducted with a modified version of AVL's VSM model with artificial latency added to test the effects on driveability in a controlled setting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control algorithms further reduce the risk of unwanted latency. When the bandwidth starts to drop, the system reacts within milliseconds to avoid latency peaks. However, with the parameters set for safe operation of the car the project could continue.

The next issue that needed to be sorted out was the communication between the circuit and AVL's facility in Graz, 80km away. Radio communications at a racetrack are pretty lively during a race weekend at the best of times, particularly with the security surrounding your own data stream from car to pit, and protecting that from hackers and nosey rival teams. But when you are running a 1200bhp electric car around a circuit, you need to be sure the communication network is secure and that it will not fail.

Corners of concern

One of the concerning aspects of the Red Bull Ring in Austria is that it is an undulating track.

'What we needed was a very stable connection, and that was quite a bit of work for our partners,' says Lohr. 'Actually these quick networks are what you need for autonomous driving in the future and all the partners were testing them successfully in the tough racing environment.'

To give Heinemann the best chance of controlling the car, the feedback from the car to the simulator had to be accurate, and in this case AVL's team worked hard on ensuring the physical cues were as good as they could be. Visual and aural cues were as important to the driver as the physical feeling through the wheel and pedals.

'We did our best to give him a real feeling on the steering and the brakes,' says Lohr. 'Together with our partners we also worked on other senses, so that the sound was right, for example. It was not like we normally work with our software, we really had a partnership between many other companies.'

Technology showcase

Heinemann's lap time was not comparable to that of Rast, at least over this run, as the team was only there to showcase the technology rather than to set lap records. While the DTM is talking about remote racing, for AVL this was not the main point of this exercise.

'It was about making the technology visual,' confirms Lohr. 'We wanted to show what was possible and give it a bit of fun for the spectators.'

Having secured the parameters around latency and network reliability, attention turned towards the car itself, and the components needed to make it physically possible to complete the lap with a virtual driver. Many of the advanced technologies

Autonomous driving?

Schaeffler believes that by 2035, around 30 per cent of all new cars and light commercial vehicles will be operated at least partially by automated system, while half of them will offer the capability for highly automated driving.

'The increasing automation of driving functions on the road to fully autonomous vehicles also imposes more rigorous requirements on chassis applications in respect to reliability and safety,' says Viktor Molnar, president chassis systems business division at Schaeffler.

'We are continuing to ramp up our activities at component and system level, and are well on track to becoming a preferred technology partner for intelligent drive and chassis solutions.'

> **» Once we had a point where the DTM was more advanced than Formula 1 and we need to get back there**
> *Gerhard Berger, manager at DTM*

AVL VSM RACE SIMULATION

After the collapse of the Class One concept following the withdrawal of its competing manufacturers, the DTM needed a quick solution, and in 2021 it turned towards the most successful production-based racing formula of all time, GT3.

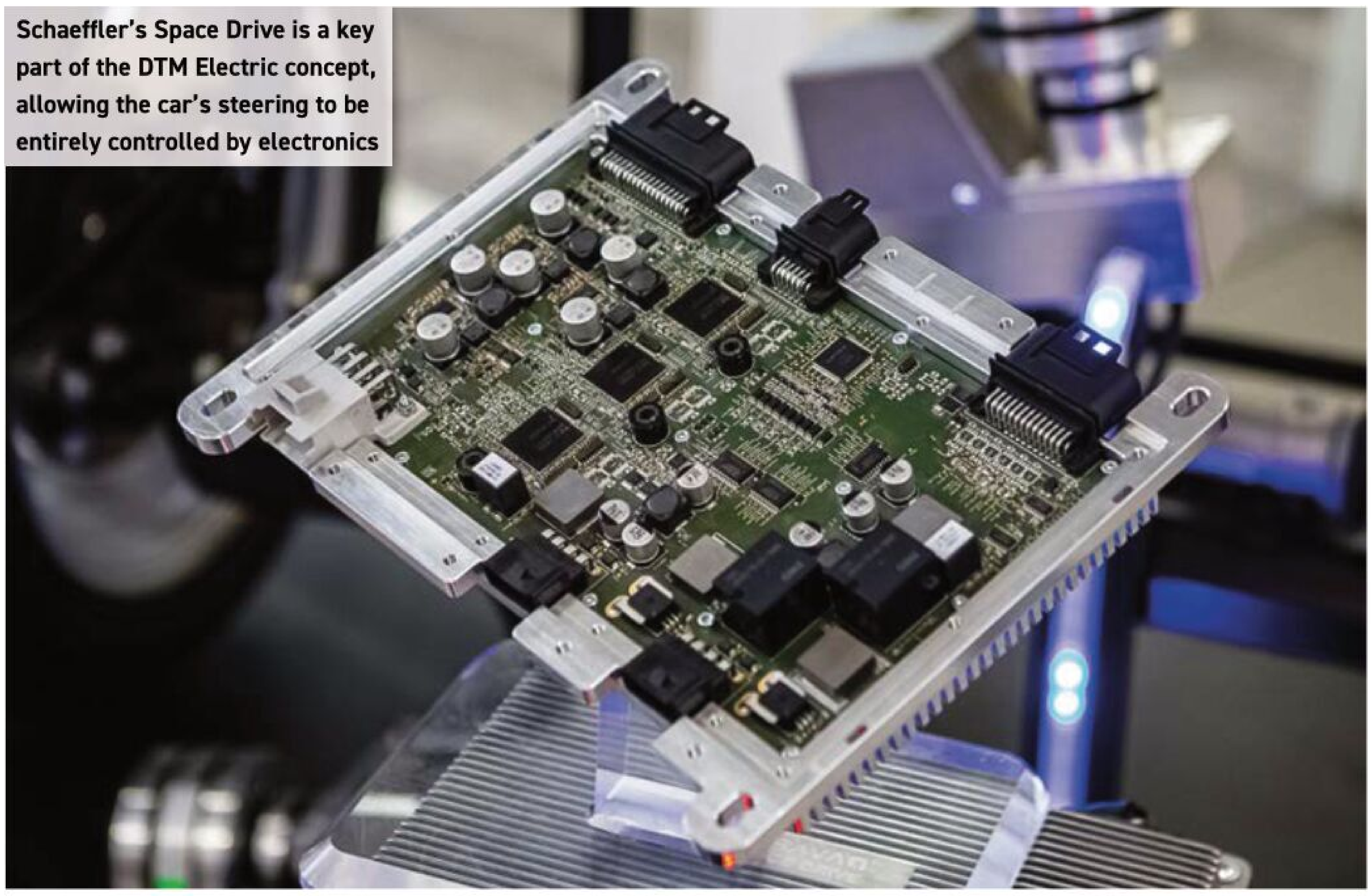
Balancing performance has become a key element in modern racing, taking over many categories in a bid to increase the number of potential competitors at a price that they can afford as it negates the development cycle that would otherwise be needed. Not only is it prevalent in GT racing, but it has also been adopted by the FIA and the ACO in its Hypercar class competing for overall victory at Le Mans. But it has to be accurate.

Although switching from a Touring Car platform to GT attracted criticism, each of the major manufacturers involved in the DTM, including Mercedes, Audi and BMW, along with Aston Martin, already had GT3 cars with which to compete, as did many others that were important to the German market, including Porsche. Not only that, but they also had customers willing to race in the DTM.

The issue was how to balance them, and in order to do so in the short timeframe that they had available they turned to AVL, which was able to use its vehicle simulation software to work out the most effective and accurate balance of performance. The VSM RACE simulation software allows AVL's engineers to simulate up to 100,000 laps by means of cloud computing in such a short time that it can be completed between practice sessions. This allows for track collected data to be processed on event, which is useful when settling any arguments from manufacturer representatives between sessions.

AVL's system relies on state-of-the-art virtual laboratory conditions, taking into account a huge database gathered from races, as well as specific data sources from test sessions, practice sessions and races throughout the DTM season. The more information gathered, the more accurate the Balance of Performance can be, and AVL's system was able to quickly and accurately map each of the cars.

In the process of creating a BoP model in a virtual environment, AVL's system is also able to exclude external factors such as temperature differences and different track conditions in determining overall Balance of Performance, but it is also able to factor these elements into the calculations in a controlled manner.



Schaeffler's Space Drive is a key part of the DTM Electric concept, allowing the car's steering to be entirely controlled by electronics

introduced into modern racecars, such as brake, throttle and steer-by-wire have all been developed to the point they are reliable.

Space Drive

Schaeffler's Space Drive, which has been tested in the NLS, racing around the Nordschleife at the Nürburgring, and which is used by Audi, BMW and Mercedes, was one of the key elements to providing the electrical feedback to the virtual driver. The system removes the steering column from the car and operates the steering wheels by electronics.

It is not necessarily lighter than a conventional system with a steering rack, and so was discounted in Porsche's Mission R, for example, but in this application it was crucial. The electronic signal was transmitted from the car back to the simulator for the key elements of control, including steering, braking and accelerating.

'The Space Drive system that has been implemented in the DTM Electric concept car is a key technology for autonomous driving,' says Matthias Zink, board member automotive technologies at Schaeffler AG. '[It has been] excellently proven, with over a billion kilometres completed on public roads.'

For the DTM series itself, it is aiming to introduce electric as one of its five pillars of racing alongside the DTM Trophy, DTM Classic, the DTM itself and DTM Esports.

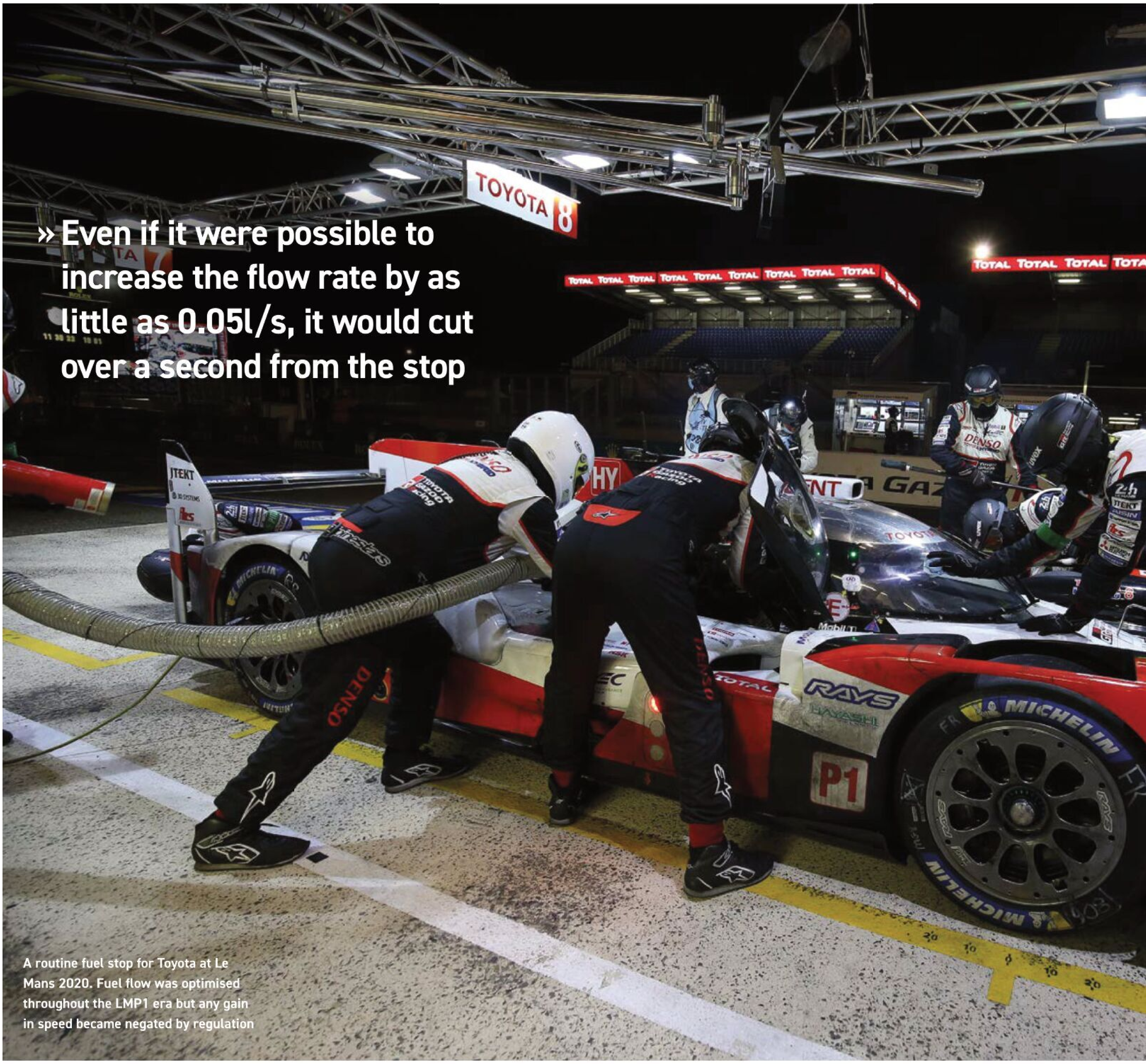
'We have to think about the platform and work on sustainable technologies,' says the DTM's manager, Gerhard Berger. 'Once, we were at a point where the DTM was more advanced than Formula 1, and we need to get back there. As a racing driver, where the power is coming from is irrelevant. What you *need* is power, plenty of it, and the skill as drivers is to handle the performance available in the right way.'

What AVL and its partners have achieved is to prove that even the location of the driver is not all important. With a stable connection, vehicles could be driven all over the world from base, which has applications in many areas of our lives. ●

Left: AVL's simulator is supported by market-leading software that allows for highly complex calculations to take place. The simulator itself can be wirelessly connected to a physical car in another building or another town. It is versatile enough to develop tyres and different concepts of cars, crucial in terms of accurately balancing GT3 cars for the DTM

AVL

Above: Tim Heinemann completed a physical lap of the Red Bull Ring from his seat in the AVL simulator



» Even if it were possible to increase the flow rate by as little as 0.05l/s, it would cut over a second from the stop

A routine fuel stop for Toyota at Le Mans 2020. Fuel flow was optimised throughout the LMP1 era but any gain in speed became negated by regulation

XPB

Go with the flow

Investigating the science and development process behind racecar refuelling

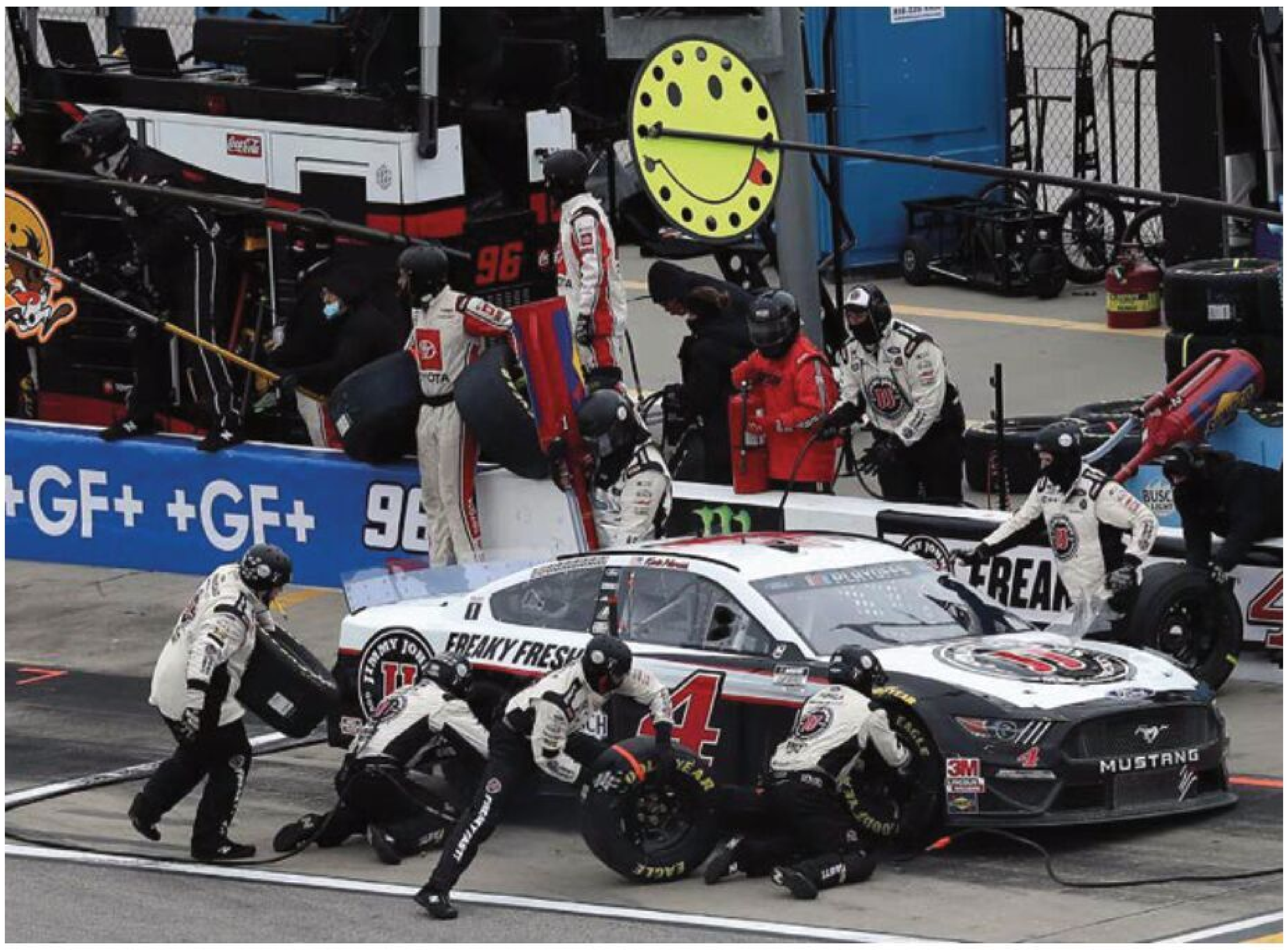
By JAHEE CAMPBELL-BRENNAN

Refuelling our cars is something most of us do as we go about our days and weeks without giving it much thought. Tank hits empty, we add fuel. Simple as that.

True to form, though, by adding an element of time pressure, motorsport takes what are seen as inert tasks and adds some flair and science to them.

The fundamentals don't change – you add fuel while evacuating air from the tank. In principle, this is not dangerous, but trying to achieve that process as quickly as possible takes us into risky territory.

As time spent in the pits equals time lost on track, there's a clear motivation to deliver the required fuel as rapidly as possible, a motivation which has



Andrew Roberts

A modern day NASCAR pit stop. The refuelling operators have to physically manouevre 50kg dump cans

XPB

Refuelling can sometimes go very wrong, as happened at Monza in 2007 with the Luc Alphand Corvette team

resulted in some famous refuelling accidents involving technician or driver error and equipment malfunction.

In efforts to improve the safety of motorsport, regulations have been updated and adjusted over the years in various ways. Refuelling is no different.

Significant investment

Using Formula 1 as an example, in-race refuelling has featured in the championship on and off many times over the last decades, before most recently being abolished in 2010 for both financial and safety reasons. Up to that point, it was an area of significant investment, culminating in a six-person operation using equipment adapted from the aerospace industry.

Being aircraft technology adapted for motorsport, the refuelling equipment was designed to a different set of engineering requirements, and featured a long stroke to reach full engagement.

'This could cause issues as, during disconnection, it was susceptible to jamming, with the probe not fully disconnecting from the car side receptacle,' comments Matt Hawkins, motorsport specialist in the connectors division at Stäubli. 'There were incidents where the lollypop man set the driver off with the equipment still coupled.

'Some of the earlier refuelling systems also suffered from deterioration of the seals due to the bio-ethanol content of the fuel, which would dry out the rubber and potentially make disconnection a little more difficult.'

Back then, fuel was pumped to the cars under pressures of up to 12 litres per second in order to deliver the required quantities in a short period of time. If the coupling, or uncoupling, isn't made cleanly with such high flow rates, a lot of fuel can be spilled in a very short period of time. And when those fuel vapours encounter hot engine and exhaust components, as Jos Verstappen and his crew found in 1994 at Hockenheim, fire spreads quickly.

There were some equally scary events in IndyCar up until the mid 2000s when the series used 100 per cent methanol, which burns with no particulate emissions (soot) to glow yellow and at cooler temperature than petrol. Add in sunlight, or bright days, and the flames are largely invisible.

Fast forward to today, and we have a near global adoption of very tight refuelling regulations to prevent corners being cut and even out the playing field.

Coupling configurations, fuel supply techniques, storage / transport equipment and refuelling conditions are all highly controlled by the FIA / ACO, IndyCar, NASCAR and IMSA, with all equipment subject to tight scrutineering.

In WEC, for example, minimum refuelling times are mandated and strictly monitored. In many cases, the pit crew isn't even allowed to touch the car, which must have the engine switched off, until refuelling is completed.

Racing advantage?

So, if everyone is using spec equipment, and working to standardised conditions, there's no advantage to be gained in the refuelling process any more, right? Wrong.

The process can essentially be broken down into five phases: 1, hustle refuelling equipment to the car; 2, coupling of male refuelling probe to female tank socket; 3, fuel transfer into vehicle; 4, disconnection of coupling; 5, technician and equipment moving clear of the car.

Each of those phases offer opportunities to optimise a refuelling stop, but also the potential to introduce risk and expense.

Almost universally, fuel is supplied to the car from a pit-located supply tank via a hose. Unless you're competing in NASCAR, you don't have a fueller running around with 50kg+ of fuel on their back!

With modern regulations banning pressurised fuel delivery, fuel relies on gravity to drive the flow. The pit supply tank is located a strict 2m above the track surface and limited to ensure the effects of gravity cannot be used to increase the flow rate by introducing a pressure head. This is something that has been adopted by the vast majority of professional motorsport disciplines.

Couplings are universally dry break, which ensures fuel physically cannot flow unless the refuelling probe is fully inserted into the socket of the car's fuel tank.

Despite their apparent simplicity, the couplings are intricate pieces of engineering designed to ensure both safety and ease of operation by the technicians.

'The refuelling head is operated by two pivoted, lever handles that are also the carry points as the pit crew member approaches the vehicle,' explains Anthony Bird, motorsport accounts manager at Stäubli. 'The internal valving design ensures a smooth transition to the vehicle's tank plug during connection and disconnection. There are safety lock pins in the refuelling head, which only unlock the levers once the probe is coupled squarely with the socket.

Stäubli

Stäubli SAF 45 refuelling connectors are widely used in motorsport today

» With modern regulations banning pressurised fuel delivery, fuel relies on gravity to drive the flow

As the levers are pushed home, locking claws engage to ensure the force required to maintain the connection is manageable and consistent throughout the fill.'

To ensure safety, the lever handles spring closed if they are released, ensuring any fuel flow is always intentional. They also earth the car to minimise the possibility of arcing and ignition of fuel vapour.

On the vehicle side, a spring-loaded plug is fitted to the entrance of the tank socket so the tank automatically seals as the refuelling probe is removed, and to ensure no fuel is spilled in the event of an accident.

Dead man's switch

Before any fuel can flow from the supply tank into the car, though, a manual 'dead man's switch' must be operated by a second member of the pit team. This is a spring-loaded ball valve located at the outlet of the pit supply tank. It's a 'fail closed' concept so, if a refuelling accident were to happen, or the driver leave the pit box with the hose attached, the technician releases the switch to stop flow out of the tank.

Once the pit crew have made the coupling and opened the dead man's switch, the fuel flows through flexible, insulated hoses. The maximum diameter is carefully regulated and ranges from 1.5in in FIA series to 3in in IndyCar. This controls flow rate and restricts the quantity of fuel in the hoses during the refuelling process.

Of course, a vent must also be provided for the gas being displaced by the incoming fuel. As this gas contains flammable vapours, it must be considered more carefully than simply a vent to atmosphere. Modern motorsport refuelling devices use a closed loop system in which the exhausted gas travels back into the pit supply tank through separate hoses of the same diameter, on the same axis, ensuring vapours have no exposure to sources of ignition.

'Coaxial design hoses feature two circular valving assemblies inside of each other, so the fill and vent hoses that are attached to the back of the refuelling head also run coaxially with the fuel delivery line inside the larger diameter vent line,' explains Bird.

If you're quick, you might then figure out that fuel delivery with this closed loop approach could potentially be 'assisted' by introducing negative pressure along the vent circuit in some way, pulling the fuel through to increase flow rate. Unfortunately, the regulators had that one covered early on.

The longest phase in the refuelling process by far is the transfer of fuel into the car, so it's also the phase that offers the largest scope for time saving.

Every second counts

'In modern WEC racing, a 100-litre fuel tank can take just over 45 seconds to fill up,' notes Giles Dawson, managing director at Aero Tec Laboratories (ATL). 'That's a flow rate of just over 2.2l/s. Compare this to a few years ago when regulations allowed pressurised fuel delivery, you could fill a 65l tank in around 3.5s, which equates to an 18.5l/s flow rate through what was then a 2in diameter hose.'

45 seconds is a long time to be sitting still during a race. Even if it were possible to increase the flow rate by as little as 0.05l/s, it would cut over a second from the stop. That might not sound like much, but over a 24-hour race, where more than 25 refuelling stops might be made, that's a

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huge advantage. Enough to motivate some ingenious techniques to gain an advantage.

As regulations dictate, orifice plate-type restrictors are mandated at the exit of the pit supply tank to control the flow rate into the hoses. The idea is to limit the flow leaving the tank to make any downstream advantages impossible. The exact diameter of the restrictor is modified on a car-by-car basis to contribute towards BoP, but for the most part is around 30mm.

'Fuel rigs are scrutinised and passed or failed by running a calibrated ball through the restrictor opening. If the ball matched the orifice size in the restrictor, it passed, but this ultimately opened the door to exploration of what could be done to optimise flow through it without interfering with that opening,' explains Dawson.

In 2018, G-Drive Racing found itself disqualified for not complying with regulations after the ACO found it was using a bellmouth opening to the restrictor plate, causing the fuel flow through the orifice in a more laminar fashion, giving enough advantage to cut seconds from the team's refuelling stops. As it turned out, this contravention of the spirit of the regulations was especially unfortunate as the team won the LMP2 category with a greater margin than the modification of the restrictor opening afforded.

As the ACO added layers of regulation to refuelling practices, so it added technology to the supply tanks, monitoring how fuel was being transferred by teams with a fuel level sensor. The supply tank-mounted sensor produced data that allowed it to determine when refuelling began, ended and whether the process met minimum refuelling times.

In the same year, Dempsey-Proton Racing had all its championship points for that WEC season invalidated after it was discovered the team manipulated the code in its data logger to falsely record an additional two seconds refuelling time.

With such extreme penalties for looking outside of the rulebook, what space do teams have to innovate?

Cool runnings

Let's look a little further back to Group C Sportscar and F1 racing in the 1980s, when teams used to cool the fuel to -30degC in order to increase its density before refuelling. Compared to fuel at an ambient temperature of, say, 20degC, this allowed teams to fit around six per cent more fuel in due to it to occupying a smaller volume in the absence of heat. Or to deliver a specified mass of fuel at a given flow rate in a shorter time period.

With tank sizes of 195 litres, that meant a potential extra 11 litres in the tank, provided they could use it before it heated up again. Cold fuel also has an added advantage in

Breda

Today, computer-controlled bowsers can automatically transfer fuel from the storage barrels in the pits to the car's fuel tank

terms of engine performance, especially when combined with a higher boost pressure, as a colder, more dense intake charges allows an engine to produce more power.

Nowadays, fuel temperature is mandated at no less than 10degC lower than ambient. Breaking this rule will result in a penalty, but that doesn't stop teams from capitalising on the advantage offered by chilling fuel before delivering it to the insulated pit supply tank.

'We use traditional vapour compression systems, together with a petrol heat exchanger in our equipment to control fuel temperature,' comments Giorgio Breda, managing director and chief of electronics and software at Breda Racing. 'We have to have precise control to avoid any regulation infringements, so closed-loop software control is a requirement, too.'

Fuel quantities are always measured by weight rather than volume in motorsport, which is an important distinction. As weight is calculated via the acceleration experienced by the mass of fuel due to gravity, this means its weight registers differently at separate circuit locations. The important variable here is the geographical latitude of the circuit.

» In the present day, developments in refuelling technology with objective to improve performance are walled off

As the earth is a slightly 'squashed' sphere, its radius is larger at the equator. Gravitational acceleration is lowest at the equator and highest at the poles (varying between approximately 9.76 to 9.83m/s^2). This means fuel scales need to be calibrated at each individual circuit to be accurate.

Development race

Regardless of how fast you can deliver fuel to the car's tank, the refill rate is locked to the venting rate but, outside of tightly controlled race conditions and regulated equipment, what room is there to develop the technology within the vehicle to aid refuelling times?

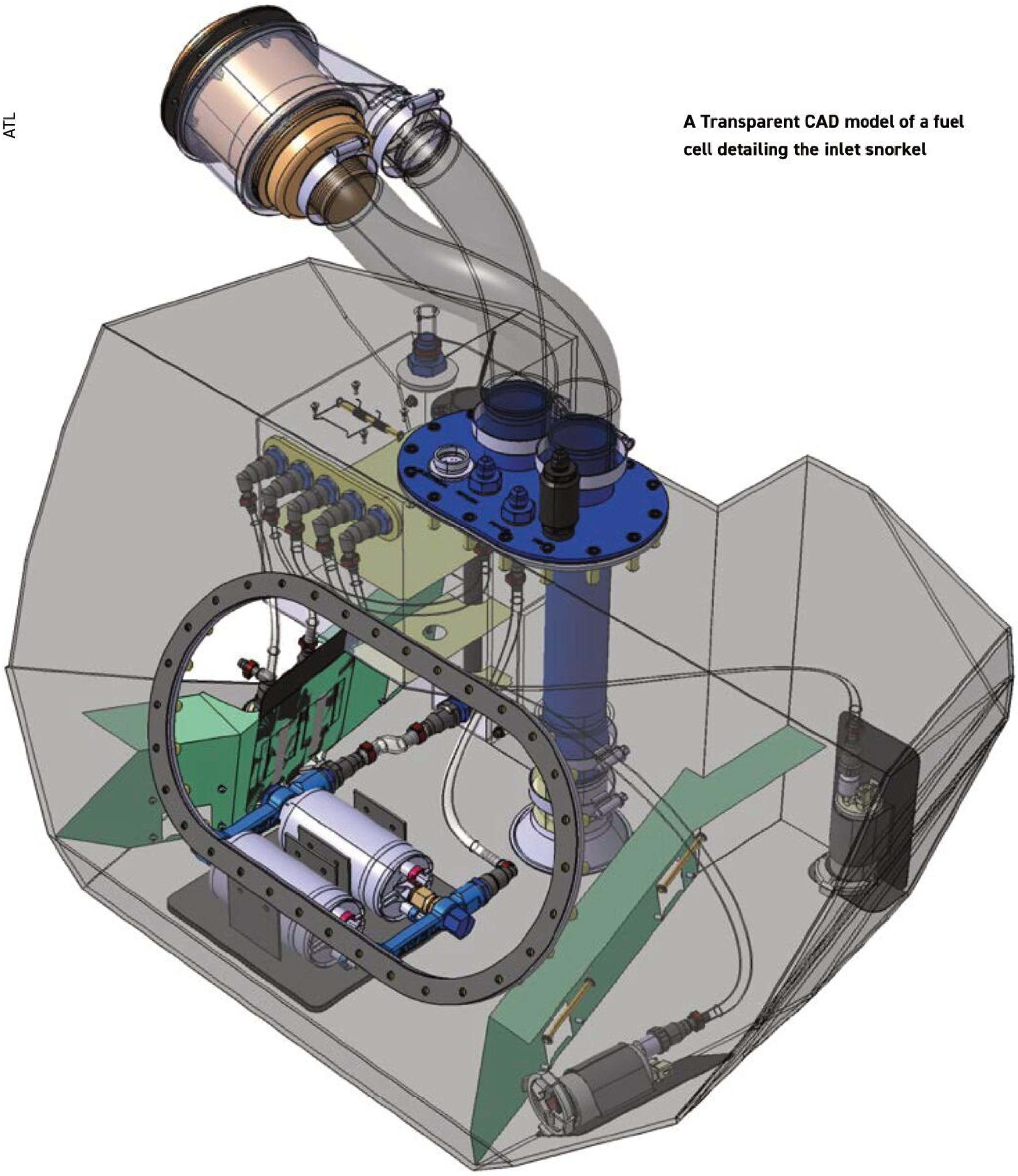
'When Porsche developed the RS Spyder in the early 2000s, there was a big focus on developing the refuelling speeds for that programme. Outside of F1, it was probably the only time it was focused on properly,' notes Dawson. '[As a result,] the Porsche was so much quicker than anyone else, which started the development race on it.'

By focusing on baffling and filler inlet locations, the turbulence and concentration of vapours within the tank can be controlled, giving benefits in that it allows the gas to exit the tank with less resistance.

'At ATL, we discovered that keeping the vent gas laminar gave big advantages here, so most efforts to increase the fill speed on the vehicle side were associated with this,' continues Dawson. 'We worked with Porsche using transparent tanks to understand the filling characteristics and things like that. Delivering the fuel below the fluid line and optimising the venting geometry helped a lot.'

With Porsche's return to WEC in 2014, even more resource was invested into refuelling, which the ACO eventually caught wind of. Feeling it was contravening cost-cutting measures, the organisation closed off those development avenues by stipulating *minimum* refuelling times.

ATL



A Transparent CAD model of a fuel cell detailing the inlet snorkel

So in the present day, developments in refuelling technology with objective to improve performance are walled off, but there is still scope for development around the ergonomics and effectiveness of the equipment to make the process more efficient for the pit crew.

Making the equipment easier to handle, automating any operations where possible and developing components to help technicians be more accurate in their fuel delivery are new, but welcome innovations.

'We design our SAF system to provide a mechanical advantage as the coupling engages, which in turn reduces the effort needed by the refuelling pit crew member as the system opens the vent and begins the fill,' explains Bird. 'This kind of design avoids the operator having to apply excessive and increasing pressure to maintain the connection as the fuel tank is filled, which is not only tiring and dangerous, but can interfere with the speed of flow.'

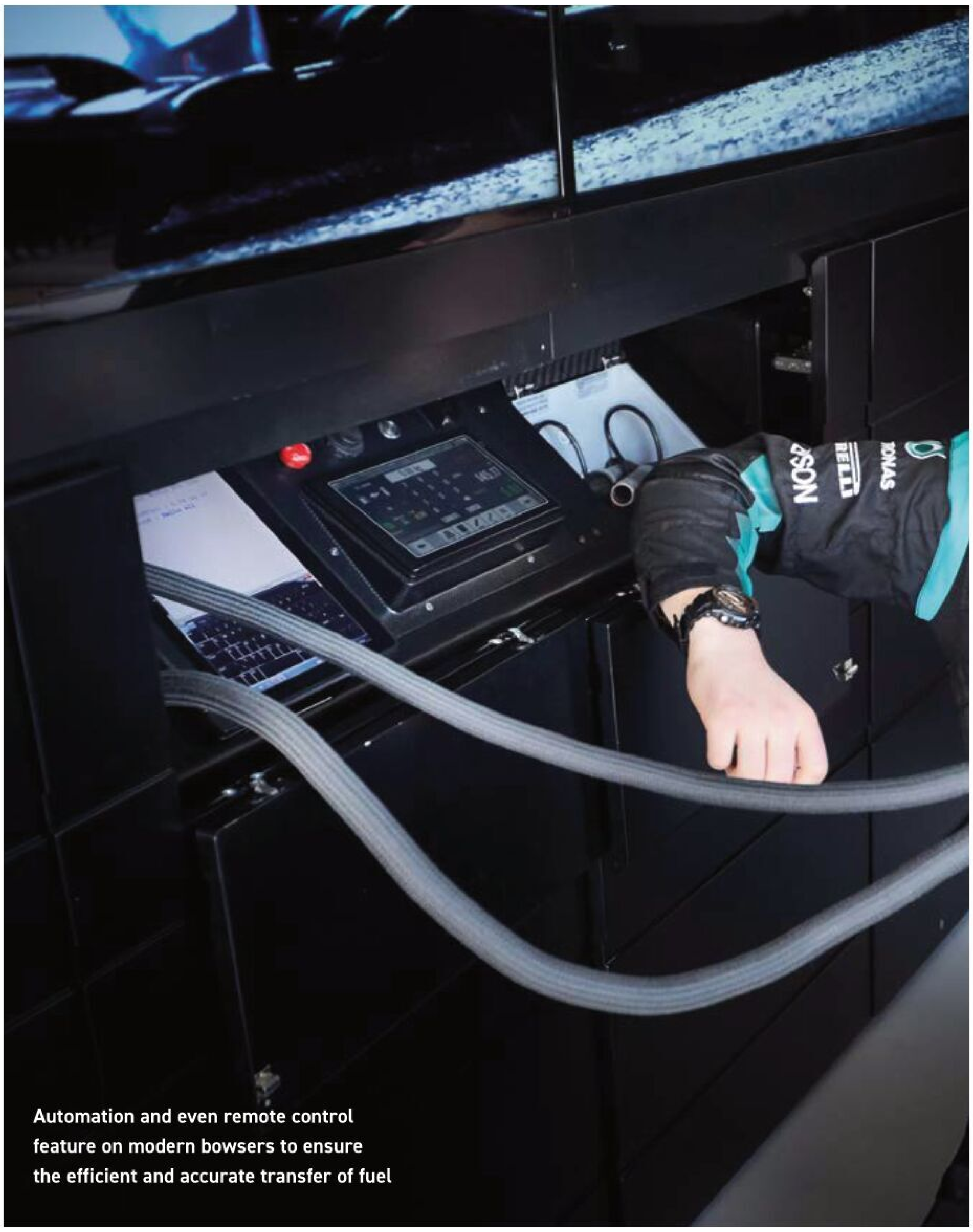
Fuel bowsers

When not in race conditions, ie practice and qualifying, and where in-race refuelling is prohibited, fuel is delivered from the main storage barrels to the cars via portable fuel bowsers, a piece of equipment which in the last ten years or so has also come a long way.

'We first got into this business nearly a decade ago now after we were asked to repair a bowser for a World Renault team,' says Derek Hodder, motorsport director at EEC.

Good ergonomics are essential to ensure the refill goes smoothly

EEC



Automation and even remote control feature on modern bowsers to ensure the efficient and accurate transfer of fuel

Breda

Timers help the operators deliver accurate quantities of fuel during a race refill

EEC

» If you want to put, for example, 20.7kg of fuel into a car, it's as easy as entering that amount into the bowser keyboard. The machine will do the rest

Derek Hodder, motorsport director at EEC

'It was using ancient technology. It had an open circuit board and relays that were underrated and would spark when fired. The fuel vent was open to atmosphere and it didn't even have a fuse from the battery. So, if there was ever a short circuit, the risk of fire was huge.'

Unsurprisingly, motorsport has now moved on from there to fully closed loop systems with automated fuel delivery, and proper circuitry.

Standard sensor equipment in refuelling bowsers today measures fuel temperature, weight (via load cells), fuel level and vent pressure, ensuring the system remains safe by shutting down automatically if a vent becomes blocked, for example. They also feature software control, which adds a level of autonomy to the process.

'Bowsers today provide a much safer method of transferring very precise fuel amounts to and from the car. Accuracy in their operation is very important to match a team's calculated fuel requirements,' continues Hodder. 'If you want to put, for example, 20.7kg of fuel into a car it's as easy as entering that amount into the bowser keyboard. The machine will do the rest, all automatically.'

Keeping up with developments in connectivity and the Internet of Things (IoT), bowsers can even be remotely programmed by the race engineer, which can help reduce workload in race weekends.

'In our higher spec bowsers, we wanted the possibility of remote equipment control to facilitate the pit crew. For safety reasons, some operations still need to be initiated at the bowser, with an operator at the dead man's button, but these developments have been well received,' adds Breda.

Time management

In race conditions, however, once the fuel is delivered from the bowser to the pit supply tanks, the refuelling technician must still manually ensure the required quantity of fuel is delivered. By precisely understanding the flow rate, it then becomes an exercise in monitoring the elapsed time and closing the flow once the specified delivery time is reached.

A neat development here is the fuel delivery timer. By providing an automatically activated second timer for the refueller to monitor, fuel quantities can be timed down to the tenth of a second by a skilled operator.

'The automatic timer activation was well received by the teams we work with,' notes Hodder. 'It can also store the last 10 fuel deliveries, which is great for record keeping. Together with the fuel bowsers, the refuelling information can be wirelessly transmitted to a computer in the pits so the race engineer can record how fuel is moving in and out of the car.'

'In the future, we see current technology filtering down to smaller racing series. We're getting a lot of orders for our entry level 'eco' bowsers in regional F3 now. Five years ago, they wouldn't have imagined using bowsers in their racing, so it's good to see a more widespread use of safe refuelling equipment, which is definitely a positive for the safety of guests in the pit garages,' Hodder concludes.

Who'd have thought the simple act of refuelling would have caused so much turbulence (pun intended) in its history? Despite ever more restrictive regulations meaning the only avenues to explore for performance improvement in the process are firmly in the grey area of sportsmanship today, it's still a technology that continues to make developments in safety and ergonomics. ●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Liquid assets

The art of delivering fuel to a racecar may seem simple, but the product has to be in perfect order in terms of performance and regulation. We look at the parts played by Stephanie Travers and En De Liow of Petronas

By MIKE BRESLIN

There is a great deal more to the job than just taking samples but, over the course of a race weekend, between 180 and 200 specimens of fluid are collected and analysed, both for compliance and as part of the race engineering strategy

It's nice to get recognition for your work. Maybe a pay rise, a promotion, or even just a pat on the back. But what about being asked to collect the constructors' trophy on the podium at the end of an F1 race to acknowledge the role you played in a Mercedes victory? That is exactly what happened to Stephanie Travers, one of two Petronas trackside fluid engineers, after the Styrian Grand Prix at Spielberg in 2020.

'I was truly honoured,' she says of the invitation. 'To represent the team and Petronas on the podium was a momentous occasion, and it's something I'll treasure for the rest of my life. It's just great for the team to recognise the hard work that we put in.'

And make no mistake, it *is* hard work. The Petronas fluid engineers arrive at the circuit very early in the week leading up to a grand prix, and it's pretty much non-stop from then on for Travers and colleague, En De Liow, until the teams leave after the race. But just what is the role of a trackside fluid engineer?

'There are two main areas we take care of,' explains Liow. 'One is making sure all the fluids that go into a racecar are in the right condition, and are what has been approved for use by the FIA – and Petronas supplies the whole suite of fluids, we're talking about the Syntium engine oil, the Tutela gearbox oil, functional fluids including hydraulic fluid, and also the Primax fuel.

'The other side of it is, throughout a race weekend, making sure the health of the car is there, and we do that through fluid analysis.'

Mobile laboratory

Their work gets underway at the track on the Tuesday before a grand prix weekend.

'We begin by setting up our lab and checking all our equipment to ensure nothing has been damaged in transit,' Travers continues. 'The next thing we do is check the fluids that have been sent out, and we check the Primax fuel first, to ensure there has been no tampering, and no contamination.'

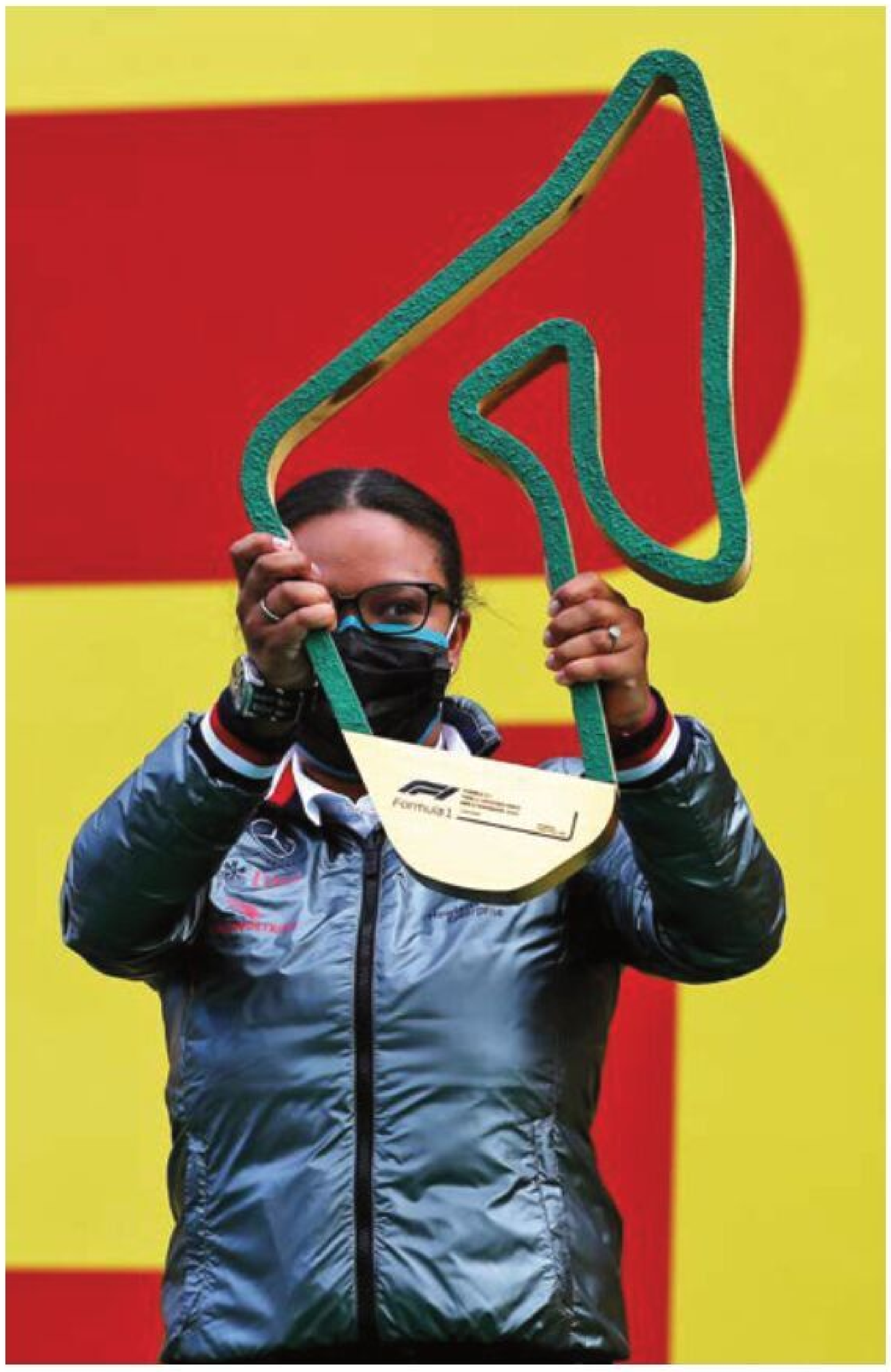
Stephanie Travers has a background in chemical engineering and has been an F1 trackside fluid engineer since 2019

En De Liow joined Travers in the Petronas lab last season. His degrees are in mechanical and automotive engineering

The Petronas involvement in Formula 1 amounts to much more than a highly visible presence on the Mercedes W12. It also develops and supplies all the team's fluids and lubricants

» The way the spectrometer works is by measuring the amount of every metal within that sample, so we can see the concentration of every single metal in the oil, and post session we can see how much wear we've had in our engine and our gearbox

Stephanie Travers


Travers with the winning constructors' trophy at Spielberg last year. The invitation to the podium was a measure of how valuable the role of these particular engineers are to Mercedes

The lab itself takes two forms over a season, explains Liow: 'Our lab is in a truck in Europe, and for the flyway races we have a unique set up, because we have the physical space and the machines travelling separately.

'The physical space travels by sea freight, and there are multiple sets of them that go around the world, but we use the exact same machine for every single race of the season, so that goes on air freight.'

The machines in question are a gas chromatograph, a spectrometer and a viscometer. The gas chromatograph is for analysing the fuel.

'It takes a fingerprint of the fuel, and we need to match that up with the approved FIA sample,' explains Travers of this part of the job. For 2021, just a single fuel specification is allowed from each supplier.

The other two pieces of vital equipment are to do with the lubricants, and come into their own once the cars go out on track. The spectrometer is used to recognise added elements present in the oils by the colours given off in the flame when they are burnt.

'The way the spectrometer works is by measuring the amount of every metal within that sample, so we can see the concentration of every single metal in the oil, and post session we can see how much wear we've had in our engine and our gearbox,' says Travers.

This crucial piece of kit has an accuracy of somewhere close to half a PPM (parts per million) when it comes to monitoring wear elements in the lubricants. 'To be able to differentiate the wear down to that sort of accuracy really means a lot to us, and to the teams, because often when you can hear or see a problem [when the car is on track] it's usually too late,' says Liow.

'We also use the viscometer to measure the viscosity of the engine oil,' Travers adds. 'We have a target we would like to be at before a session starts, and then we will use it to see how the oil has changed throughout the particular session. It's a test where the oil is sent into the machine, and then it's heated up to 100degC.'

Change of focus

After setting up the equipment, and the initial fluid testing, the focus switches to the cars on the Wednesday before the race. While Petronas' involvement is obvious from the logos on the Mercedes, it is actually also the fuel and lubricant supplier for all teams running the Brixworth PU, so that includes McLaren, Aston Martin and Williams. This means the two trackside fluid engineers have eight cars to look after in total.

'The fuel goes from the drum into the rigs for the cars, and we do another level of checks

En De Liow in the Petronas mobile lab talking with Lewis Hamilton. Note the various test equipment in the background

» **You can liken it to taking blood tests, and having your regular health tests at the doctors. That's basically what happens throughout the weekend**

En De Liow

to again make sure there is no contamination in the rigs themselves, and there are no problems with the filters etc.,' says Liow.

'We also test the fresh engine oil before it is put into the car. So we have all these checkpoints that a fluid has to pass before it actually has to deliver performance.'

The analysis part of the job begins on the Thursday before the race, but not before one final check is made.

'Thursday is the start of our race weekend, and we begin then to analyse samples from the cars,' says Travers. 'We will take a fire-up sample of fuel. Once we have had the first fire-up and everything is settled, we take a sample just to check again. We're checking there's no contamination and everything is okay, and we're ready to go on that front.

'We're not going to get disqualified because of non-compliance with FIA regulations, and that's the final check before we go into the weekend. The FIA can come in at any time to sample our fuel and oils, so this final check is very important.'

For meaningful lubricant analysis, some baseline samples also need to be taken.

'They will put the engine oil into the car, that circulates round, and then we take our fire-up sample,' explains Travers. 'That first sample is very important as it gives us our baseline before the car goes out. We always have an engine oil fire-up sample and a gearbox oil fire-up sample. We then analyse those within the spectrometer.'

Health tests

It's this sampling and comparing that makes up the bulk of the work throughout the rest of the event, with the trackside fluid engineers typically taking between 180 to 200 samples over a grand prix weekend.

'You can liken it to taking blood tests, and having your regular health tests at the doctors. That's basically what happens throughout the weekend,' says Liow.

The Petronas engineers are continually testing fluids over the course of a grand prix weekend to monitor the health of all the racecars they look after

» **We're not going to get disqualified because of non-compliance with FIA regulations**

Stephanie Travers

'We collect data from the used oils, and then we can see what's happening on track and how that's affecting the hardware. Then you reach back both to the guys designing the hardware and running the hardware [at the teams], and also to our colleagues in Turin [lubricant development] and in Malaysia [fuel development] developing the fluids. This is important data for them to keep on improving the products.

'So, from Friday through to Sunday, we will take used oil, and then when they flush the system and put in new oil, we will repeat the process of collecting a fire-up sample, which again is our baseline, and then collecting the used oil after a session.'

It's all pretty relentless then, but then most jobs in F1 are high pressure, it comes with the territory. Here, though, there is the added stress of looking after four demanding teams.

'We try to keep everyone happy, but sometimes three teams can turn up at your door at the same time. That's when you just have to say, "We're going to do it as fast as we can, and we will give you the results the moment they are available,"' says Liow.

Being prepared for this sort of stress is a key aspect of the job. 'About 80 per cent of the time you are doing all the things to prepare for that 20 per cent of the time when it really gets stressful, where everything is very time limited and there's no room for error,' says Liow. 'I think overall, I would say that's the most challenging part of the job.'

Inner cool

'At that time in the lab, we are usually at our ultimate level of focus. We have reached a level of communication and understanding,

Living the dream

Stephanie Travers and En De Liow might have been in F1 for a little while now, but they both agree that working in the paddock never gets old, even if it does get a bit heated at times.

'The most exciting part for me is being in the heart of the paddock, being able to see these exciting machines going around, and just knowing that I'm part of that,' says Travers.

Liow agrees: 'There are times when you stand in the garage. Let's say at the start of the session, right before the cars pull out, and everyone's on standby, everyone's super focussed. That's when you pinch yourself, and it's like wow! I'm in the presence of greatness, I'm in the presence of some truly amazing people to be working with.'

and we have the right processes and tools in our arsenal, so we can do our job in the knowledge that the other person is doing their job at the same level.

'The most important thing for us is to keep our inner cool, stay calm, and take on these challenging times.'

This ability to say cool and calm was something Petronas was obviously looking for when it hired Travers and Liow, both having come through its Global Talent Search, which was first run in 2018 and attracted 7000 applicants. Travers won in 2018, and Liow in 2019, each of them arriving in the F1 paddock for the following seasons.

'[This role] goes beyond technical knowledge and skills,' says Liow of the talent search experience. 'After all, it's a team sport and communication and ability to work well in a team is absolutely crucial. There are different challenges throughout the recruiting process to put pressure on you, to test you out in different ways, and also to help you understand how you can work with others in difficult scenarios.'

As an example, one of these challenges was a treasure hunt in Kuala Lumpur, to line up the deciding final interview with the Petronas Lubricants International CEO.

Clearly, not everyone will win a talent search, so how should others go about landing a role as an F1 fluids engineer? One way would be to find work in a fuel company that has a motorsport involvement first, says Travers: 'If they study chemical engineering, or mechanical engineering, and if they work for Petronas, for example, people will have the opportunity to ask to go into Formula 1. And they may be granted those opportunities depending on whether the timing is right.

'We like to bring fresh talent into the sport, so there are definitely opportunities by going and working for a fuel company.'

Engineering minds

It's interesting that Travers mentions both chemical *and* mechanical engineering as a route into motorsport fluid engineering, as this is mirrored in the Petronas trackside team, with her studying chemical engineering at University of Bradford (BEng) and Imperial College London (MSc in advanced chemical engineering), while Liow concentrated on mechanical engineering at the University of Massachusetts, and also the University of Virginia, before moving on to an MSc in automotive engineering at Coventry University in the UK. He also worked as a mechanical engineering intern at Lotus, and then helped to develop lubricants at Petronas in Turin before winning the talent search.

Liow believes that having a background in mechanical engineering, and then working in fluid development, has been useful. He also says that, for similar reasons, a role as a trackside fluid engineer is a great starting point for gaining other work in motorsport, as the skills learnt are quite transferable.

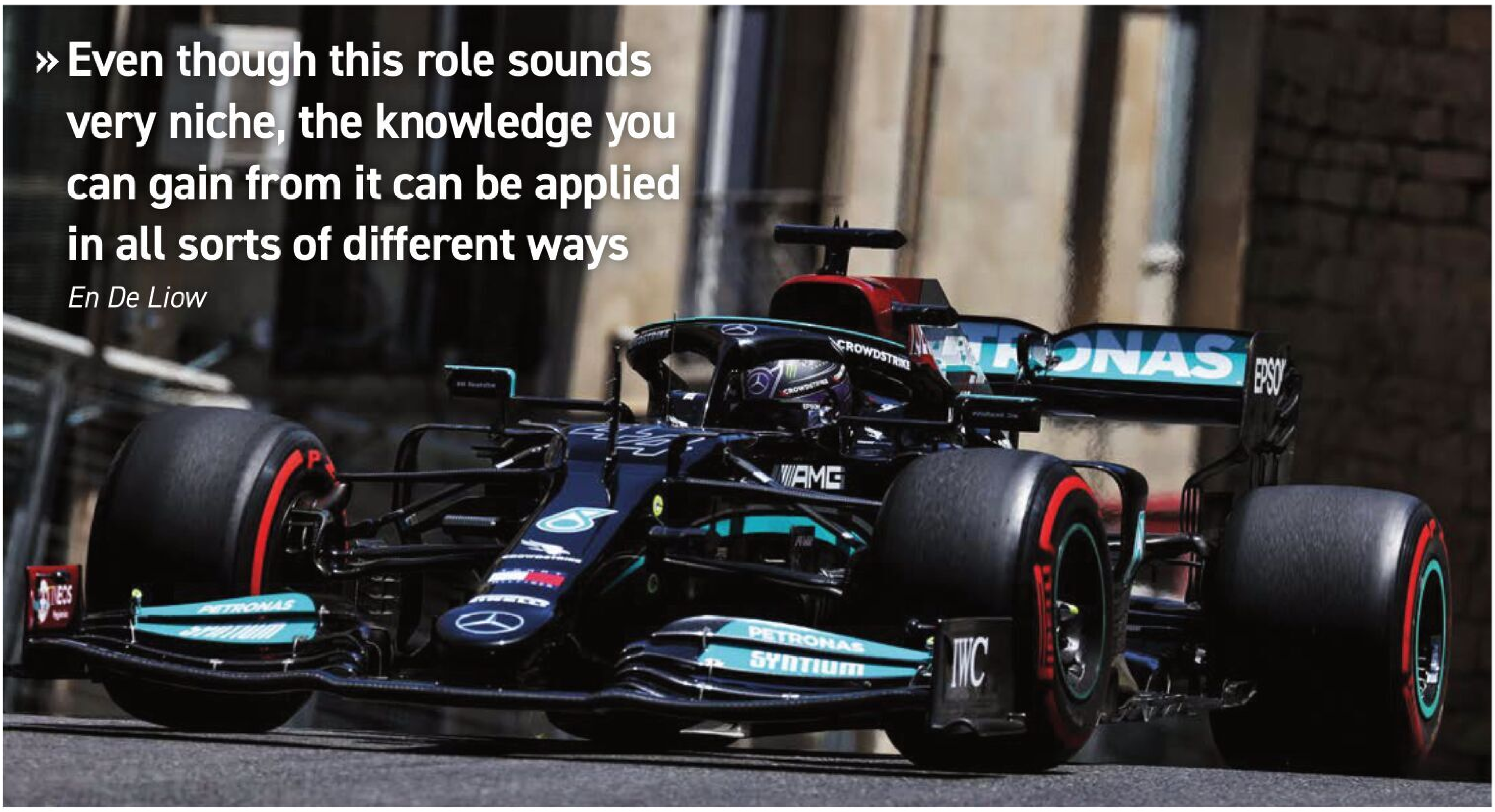
'It opens up the options, no matter which path you started on. You have a broad view between the worlds of fluid development and hardware, but you also have a deep insight into a lot of the mechanics that go on in the intersection of these two worlds, and that's certainly a piece of knowledge you can take with you down either road.

'To give you an example, I could go back into fluid development knowing more about hardware, and knowing more about how it operates in high stress environments.

'We can equally go down the other path and say we've understood, based on these types of fluid properties, the reaction you would have on gears, on pumps, on valves etc. and then go down the design path on the hardware side.

'And so, even though this role sounds very niche, the knowledge you can gain from it can be applied in all sorts of different ways.'

It's this 'intersection' between the fluid and the mechanical that makes this work so fascinating. On top of that, who knows, do a good job and one day you might even get to stand on the podium. ●



Petronas supplied to eight cars on the Formula 1 grid in 2021, including McLaren, Aston Martin and Williams, meaning the two Petronas engineers had very busy race weekends

Buckell up

There are few in the British Touring Car Championship paddock as experienced as Steve Buckell, but what exactly is the West Surrey Racing chief mechanic's role?

By MIKE BRESLIN

It's the first of the three British Touring Car races of the day at Oulton Park at the beginning of August, 2021. The West Surrey Racing (WSR)-run BMW 330i M Sport of Tom Oliphant is tapped into a spin by a rival car at Lodge Corner, and then collected by another as it lies prone across the track. It receives two crunching hits, one to the back and one to the driver's side. In the words of the team's chief mechanic, Steve Buckell, the rear end is 'under the windscreen'.

If this was a road car, it would be heading for the scrapyard, no question. But this is the BTCC, and this is WSR. There's about two hours until race two, and it's impossible to make the required repairs in time for that, but four hours before the final race of the day, and the car missing two races is simply not an option.

This is the time when a BTCC chief mechanic really needs to take control. Buckell did so and, remarkably, and thanks also to help from chassis specialist, Willie Poole Motorsport, the car was back out for the last race of the day, where

West Surrey Racing's chief mechanic, Steve Buckell, (left) has been with the team since 1989

» If I'm running around panicking, then everyone else is running around panicking

Bresmedia

One of two heavy impacts in the first race at Oulton Park, which all but destroyed the rear of Tom Oliphant's BMW. Amazingly, the WSR crew managed to repair it in time for race three

BTCC

Oliphant fought back from the back of the grid to a creditable 14th position.

It was an extraordinary turnaround, given the severity of the shunt, but for WSR's chief mechanic it was largely all about keeping calm. 'If I'm running around panicking, then everyone else is running around panicking,' says Buckell. 'But I'm relaxed, mainly because I trust the people we have working for us. Every person out there has a role to play. In this kind of situation, everyone knows their place, and everyone helps out, I just oversee it all.'

It's a part of the job he doesn't wish for, but relishes when it happens. 'Of course, you never want these things to happen, but when they do there's a certain amount of adrenalin,' he says. 'You do enjoy it, even if the car has been crashed on the Saturday and you need to work into the early hours of Sunday to get it ready for the races.

'If you don't like working in this sort of environment, you're in the wrong job.'

Crisis management

Buckell also has his experience to fall back on, when it comes to dealing with a crisis. 'I've been in racing for so many years, and during that time there have been so many accidents and problems to fix and solve, I'm just used to it.'

Indeed, his motorsport career started in the 1980s, when he became involved with Ronnie Grant Racing – a privateer Formula 3 effort – while still working as a garage mechanic in Clapham, south London. From there, he moved on to West Surrey Racing in 1989 and, a brief sabbatical aside, has been there ever since. In that time, he's worked as number one mechanic for drivers such as Mika Hakkinen and Rubens Barrichello while the team was in F3, and then on the BTCC programmes since 1996 (see box out on p83).

He's held a variety of roles in the series, including transmission technician during the Super Touring era, before taking on the job of chief mechanic at the start of WSR's MG / Rover BTCC programme 20 years ago.

Multi-talented

Perhaps because he has been with the team for so many years, and has taken responsibility for so many things over time, Buckell's role is not as well defined as it might be, though in a nutshell he describes it as: 'I'm in charge of anything mechanical. I oversee the work on all three cars. Anyone on the shop floor, they're all experienced, but they will come to me if there's anything they're concerned about.

'I'm not on a car, so I don't spanner a car, but I still do a lot of hands-on work. I fabricate, machine, I build the dampers, dyno the dampers, and I do the electrics, making sensors and doing the wiring. Right now [during *Racecar*'s visit to WSR's Sunbury-on-Thames HQ] I'm fabricating doors and welding exhausts up, for example.'

He concedes that chief mechanics on other BTCC teams might not have such a broad job description, though. 'I think I have more hats than most, but I like to do a bit of everything. I love the variety of my job, and I suppose that's why I've never bothered to do anything else, really.'

Repeat business

When it comes to overseeing the day-to-day work at WSR, there's a certain pattern, which might be expressed as: race, strip down, assemble, race, repeat. 'After we've run the cars, each one of them gets stripped down and checked. I don't know if every team does that. If you go out to the shop floor now, the subframes are out, and it's all just starting to go back together to be ready for the next race.'

The two subframes are controlled TOCA parts in the BTCC, incorporating controlled

» I love the variety of my job, and I suppose that's why I've never bothered to do anything else

suspension, brakes and transmission, with the front subframe attached to specified rollcage locations. The 'cage itself is designed in house by WSR using the latest CAD programmes.

Another large part of the work undertaken at the workshop involves car builds in the off-season, when a new model comes along, which last happened before the start of the 2019 season when WSR switched from the 125i M Sport to the current car.

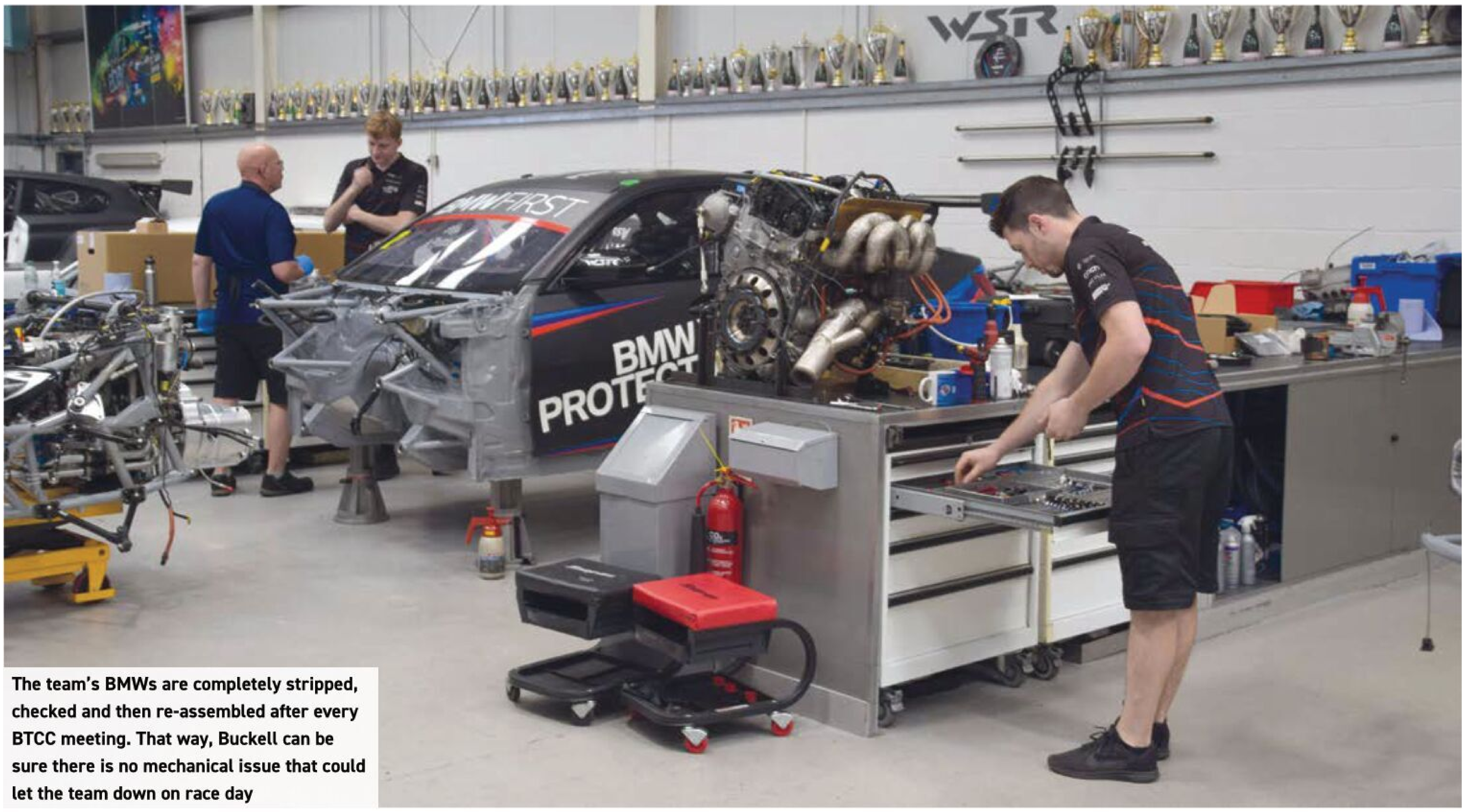
Over the 2020 - '21 winter, the team also built a couple of customer BMW 330i M Sports for Ciceley Motorsport.

While it's no surprise to hear Buckell oversees the build process, it's interesting to note that he's involved much earlier, always thinking of every possible eventuality, and this is where experience really counts.

Forward thinking

'A new build is always a challenge, turning up for the first race not knowing what you've got and all that. But I'm always confident that we've thought of everything before it leaves here. Every wire, pipe, tube… anything that might fret or rub through, is already taken care of in the design and build of the car.'

A good example is the headlights and tail lights and how they work with the Cosworth control-part harness. 'We use OEM lights, and we have them connected up to the chassis harness, which is the championship harness we have to run. But if there's a crash and it



The team's BMWs are completely stripped, checked and then re-assembled after every BTCC meeting. That way, Buckell can be sure there is no mechanical issue that could let the team down on race day

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goes through all the metal and cuts through the harness, we're in trouble, as the lights need to work for the car to run on track. So, during the build process I need to make sure there is a way we can change all that quickly.'

The same goes for many of the larger parts on a new West Surrey Racing racecar: 'With the design team, engineering-wise, I look at how the car is going to come apart in an accident, and we try to build it to make it as user friendly as possible.

'I love that side of it. Because, for me, I helped design that car in some ways. Not on CAD, not sitting up there doing drawings and whatever, but physically. I can say to the designer, "I'll make one, here it is, now go and draw it."'

Advisory role

At the track Buckell's role is more hands off, he says, until there's a crisis.

'I'm there in an advisory role for a race weekend, where if something comes up, or there's an issue, they'll come to me with it. I stand around with a cup of tea in my hand, and that makes me look calm and everyone thinks things are under control, and generally they are.

'But this [the workshop] is where it's won or lost. You leave here and, if you have ticked all the boxes, all should go well at the track.'

During a BTCC weekend, the cars are tended by technicians – they are rarely called mechanics these days.

'We have a number one and a number two dedicated to each car. At a race meeting we have a dedicated data engineer and a race engineer for each car. Data engineers are generally weekend only, but with our race engineers they are working in the background prior to each round, too.'

Some of the technicians are self-employed, but they do work at the Sunbury base in the week for much of the year. WSR employs around 12 people full time and a further 15 on a part-time basis. And if you're thinking of applying for a job there, it's worth noting that, above all, Buckell wants the technicians that come to WSR to have practical skills.

'I suppose everybody is doing all sorts of degrees in engineering and motorsport these days, and some of them are very good. But

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The engine is fitted back into the front subframe of one of the team's three BMW 330i M Sports

» I helped design that car in some ways. Not on CAD, not sitting up there doing drawings and whatever, but physically

» I get my reward with my cars finishing the race because they are mechanically sound, and that for me is everything

I prefer people who are hands on, who've actually worked on cars. I've had people come to us in the past who have got degrees and they can't even hold a screwdriver.

Next generation

'We have a very good thing here, a scheme with Brooklands College, where we bring youngsters, 16 and 17, in for work experience. They do a week and we see whether they are interested, or whether they wander around with their hands in their pockets. We pick those who are good and show initiative, then ask them to come back and do a couple of days here and there between their studying. Then we take them on race weekends, use them as a number three technician – cleaning, a bit of brake building – and then they slowly build up their knowledge and skills. Most of the people here now are ex-Brooklands. They have come through that scheme, and I'm quite proud of that.'

As for those wanting to build a career as a BTCC technician, and perhaps ultimately a chief mechanic, Buckell's advice is crystal clear. 'It's all about experience. Getting trackside. Anyone who has got some spare time at the weekend, just go and work on a team. Clean the car, get involved, see what's going on, ask questions and get stuck in.'

For his part, Buckell is still getting stuck in, and reaping the rewards, which for him is not simply success on track, although that's obviously a large part of it.

'I get my reward with my cars finishing the race because they are mechanically sound, and that for me is everything,' he says. 'If we don't have the performance there, it isn't because the car hasn't been assembled properly. That's down to the engineer, the driver and circumstances on track.

'For me, when I finish work on the Sunday night of a race weekend, and the cars are good, it's job done.'

And then, of course, it's time to think about stripping them down, checking everything and re-assembling them for the next event, the cycle starting all over again. Not that Buckell minds this at all.

'My job is like a hobby I get paid for. That doesn't mean I'm looking at it in an unprofessional way, it just means I love doing what I do.' ●

West world

The 2021 season was a big year for West Surrey Racing, as far as significant numbers are concerned, because it marked its 40th year as a race team, and 25 years since it first entered the British Touring Car Championship. To further add to the celebration, it also scored its 100th win in the BTCC at Knockhill in August.

And in the foyer of the team's impressive Sunbury-on-Thames base – a facility where it's genuinely difficult to find wall space not filled with trophies – there's a reminder of its glorious past, a Ralt RT3 Formula 3 car resplendent in the livery of the team's first season, when it also scored its first championship win with Jonathan Palmer in 1981. It's a car the team's chief mechanic, Steve Buckell, has personally restored.

After that successful debut season, Dick Bennetts' team went on to win four more British F3 titles, running future F1 stars like Ayrton Senna (1983) and Mika Hakkinen (1990), before switching to Touring Cars in 1996. Since then, it's run factory-assisted Ford Mondeos, Honda Accords, MG ZSs and, from 2007, BMWs in the BTCC, along the way picking up four overall drivers' titles.

There was also a single season of the highly successful F3000 series in 1986, and three years of the ill-fated A1 GP in the 2000s.

When pressed on his favourite season, Buckell pauses for quite a while before saying: 'I think the 2009 Touring Car win [with the BMW 320si], when Colin [Turkington] won his first drivers' championship, because we won everything: independent driver, overall driver, independent teams and overall teams.'

As for unusual jobs he's had to do, Buckell pauses for a moment before recalling filing down the edges of the soles of Hakkinen's race boots so the Finn would fit in the team's Ralt RT34 F3!

But in as diverse an activity as motorsport, does he have any regrets, sticking with one team for over 30 years?

'People ask me why I haven't gone and done this or that, and my only regret is that I didn't do Le Mans, because I think I'd like the challenge. I don't have any regrets about not doing Formula 1.'

You can't help thinking that WSR boss, Bennetts, also has no regrets about Buckell never having done F1.

Ralt RT3 Formula 3 car parked in the foyer of the team's west London HQ is a reminder of WSR's first season in 1981. It was personally restored by Steve Buckell

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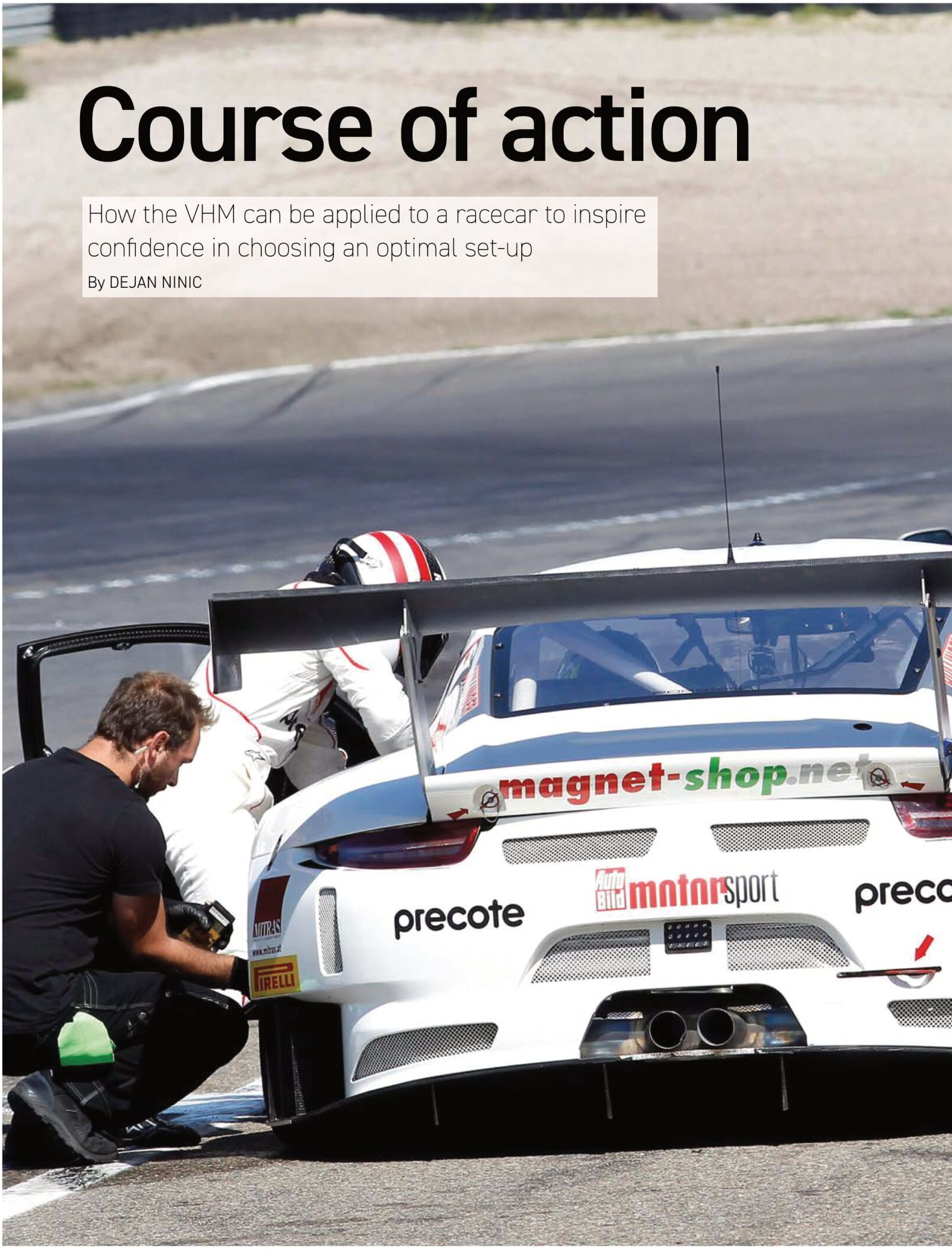
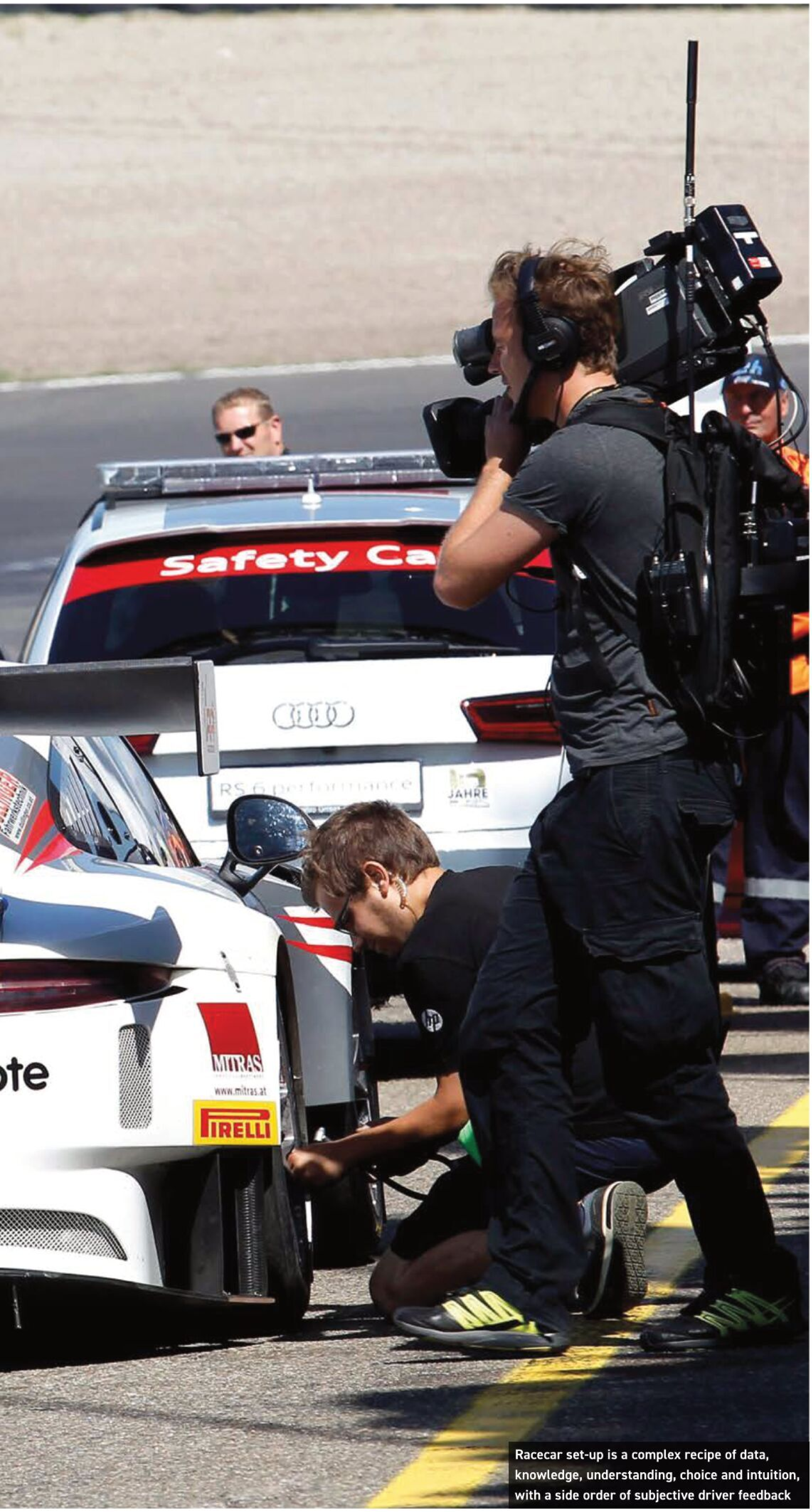
Course of action

How the VHM can be applied to a racecar to inspire confidence in choosing an optimal set-up

By DEJAN NINIC





Racecar set-up is a complex recipe of data, knowledge, understanding, choice and intuition, with a side order of subjective driver feedback

A poor handling racecar seems an impossible occurrence these days, considering the access to gigabytes of logged data, tyre modelling and simulation tools, including CFD and lap time optimisation. It seems that with a small amount of testing and the huge array of information available, a car's set-up and handling can be optimised in minutes, rather than the weeks or even months it used to take.

However, despite all the information we gather and analyse, it's still easy to lose your way in the minefield of set-up options, and convince ourselves we still don't have enough information. I know, because I've been there and done exactly that, thankfully more so earlier in my career than recently.

» Setting up a car is, fundamentally, a decision-making process, albeit a highly technical one

It is not difficult to imagine how a last-minute adjustment in pit lane during a qualifying session could induce just enough instability that a collision with a barrier or competitor would be unavoidable. So, when there is so much at stake, including the life of the driver, why do we still hear interview response such as, 'We struggled to get the set-up right', or 'The car could have been better…'?

Value scheme

Setting up a car is, fundamentally, a decision-making process, albeit a highly technical one with the aid of detailed logged data and subjective driver feedback. Simply put, the course of action is as follows: firstly, understand the problem and the decisions that need to be made; secondly, list the available choices; thirdly, assign a value to each choice so they can be sorted by that value scheme.

A thorough approach would also consider the most likely outcome if the first choice was actually implemented, as well as the outcomes of any other highly valued choices. In the domain of race engineering, there are many expert engineers who can predict the change in handling for even the most detailed set-up changes, but they can still make the wrong choice in the heat of the moment. Likewise, there are many successful engineers who can intuit accurate set-up changes based on experience and gut feeling, but could never explain why or how they came to that decision. The latter find it simple, almost natural, to make a certain change, but the former often gets lost in the number of available choices and their 'pros vs cons'.

Can the set-up decision making process therefore be made simpler, or is it really as difficult as Max Verstappen leads us to believe? Indeed, as this article aims to explain, the process is actually quite simple, although that does not mean it is necessarily easy.

Handling traits

The Vehicle Handling Model (VHM), as shown in **figure 1**, was introduced in *Racecar Engineering* V30N7 and is one such simple method of assigning value to each set-up choice. The value scheme is based on summarising and ranking vehicle handling into four categories: stability, response, balance and grip. For their detailed definitions, the reader is directed to the aforementioned V30N7 article, keeping in mind the description is more important than the pronoun assigned to it. For the purposes of this piece, I'll cover them briefly again here.

Stability is the car's ability to return to its intended path after an intended or unintended disturbance. It is of primary importance because without stability the driver lacks confidence and will drive the car with reserve.

Response can be considered as the time delay of an inertial change, often how long a car takes to 'set'. However, when the response relates a given inertial output (say, yaw acceleration) to a driver input (say, steering angle) we can say response is the measure of how much control the driver has. More control will give more confidence.

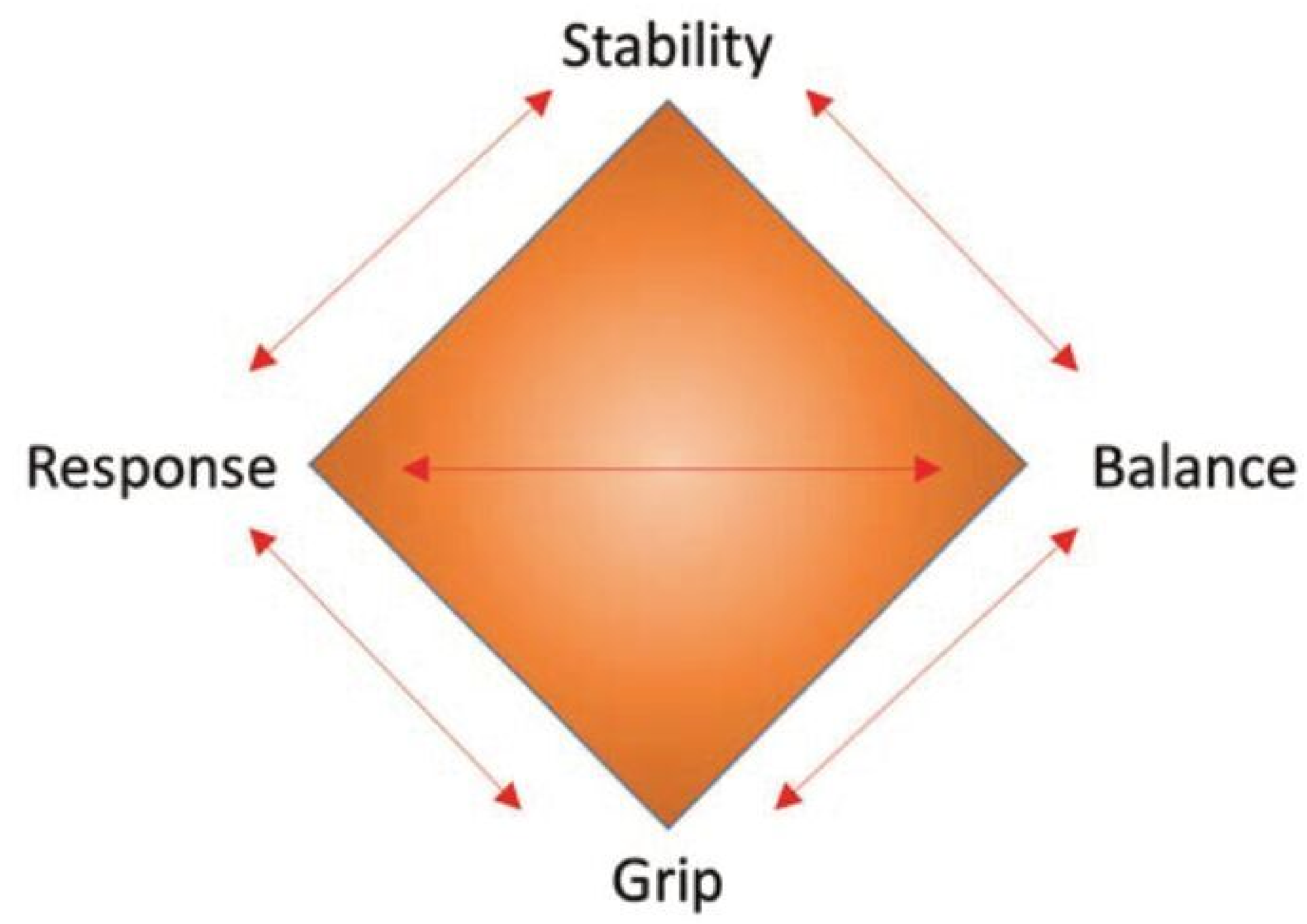


Fig 1: The four parameters of the Vehicle Handling Model

Balance, for this purpose, refers to the well-known states of understeer / neutral steer / oversteer, only that within the VHM balance can only be assessed when the car is cornering at maximum or near-maximum lateral acceleration. A worthwhile example here is turn-in understeer, which is commonly considered a balance issue, though is actually a response issue in the context of the VHM.

According to most definitions, an unbalanced car deviates off the intended path when approaching the limit of lateral acceleration. If the front axle slides at the limit, we call that understeer. If the rear slides first, we call it oversteer, and if both axles slide simultaneously, we call the situation neutral steer. In all cases, poor balance results in reduced peak lateral acceleration.

Last in the value scheme, but still of significant importance to performance, is grip. Here it is defined as the car's ability

» It is in the abundance of a strength that lies the solution for the weakness

By far the most sensitive set-up adjustment is toe, either in or out

Table 1: Typical set-up options for a Porsche Supercup 911 GT3

Set-up change				Typical step adjustment	
Tyre pressure	**F**	1.85	bar	0.05	bar
	R	1.9	bar	0.05	bar
Ride height	**F**	78	mm	0.5	mm
	R	100	mm	0.5	mm
Anti-roll bar	**F**	3	of 7 (1 is softest)	1	position
	R	6	of 7 (1 is softest)	1	position
Camber	**F**	-4.8	degrees	0.2	degrees
	R	-4.0	degrees	0.2	degrees
Toe in	**F**	-0.08	degrees per side	0.06	degrees per side
	R	0.28	degrees per side	0.06	degrees per side
Brake balance		47.6	per cent front (pressure)	0.2	per cent
Springs	**F**	240	N/mm	Not adjustable	
	R	260	N/mm	Not adjustable	
Wheelbase		2463	mm	Not adjustable	
Wing		9	of 9 (1 is flattest)	1	position

» There are certain set-up changes that have consistent repeatable outcomes for most conditions

to accelerate (referring to the car as one entity) rather than the grip produced at each contact patch. Indeed, the individual contact patch grip is important so we will refer to it as traction.

Strength vs weakness

The VHM highlights that the coupled nature of these categories is the key to selecting which strength to trade off to improve a weakness. It is in the abundance of a strength that lies the solution for the weakness, and this forms the required connection of the value scheme to the present problem.

The good news is there are only four categories that need to be assessed, and often the trade off becomes obvious.

The bad news, for some, is knowing which available set-up change will affect the targeted handling category. To understand those relationships, you do not need to have a degree, but a reminder to understand stability, response, balance and grip when out testing with the car. The following example will explain how the VHM can be applied to a car.

To guide us through this part of the process, we will choose a very common one-make racecar, a Porsche 911 GT3 Cup (991 II), as seen in the Porsche Supercup Championship, a common F1 support category. To some, this factory-built racecar has relatively limited set-up options, but the teams preparing these cars for racing know this very fact demands a deeper understanding of the car and tools to learn its set-up intimately and be able to find improvements. Despite the limited choices, it's still very easy to lose one's way.

Set-up options

Table 1 lists the available set-up options for this example. If we use the factory-recommended starting set-up, also listed in the table, we can discuss the handling effect of each available set-up change on our four handling categories. At this point in the discussion, it is very important to emphasise that these are *my* comments, and they are not in agreement or disagreement with the Porsche factory. Experienced engineers know well that one single recipe for set-up cannot possibly exist. However, there are certain set-up changes that have consistent repeatable outcomes for most conditions, and it is these I aim to present here.

Additional toe in at the rear will improve stability, but at a trade off with response and balance. Tyre temperature increases, too

Tyre pressure

The first set-up value is tyre pressure, and it is the most important. The set-up sheet requires the tyres at these pressures when aligning the suspension to ensure a consistent measurement of ride height. This pressure is not far from the recommended target pressures when the tyres are hot and stabilised. It would be agreed that, for a given camber angle, given mass / vertical load and given operating temperature, there is an optimum tyre pressure. As tyre pressure is a strong parameter in the shape of the contact patch, it will have a significant effect on the traction available.

Tyre temperature distribution measurements, tyre wear measurements and the evolution of the car's handling as the tyre heats up and builds pressure will all be a guide to determining the ideal pressure. It is very possible that an errant over pressure or slow puncture could be the cause of poor handling, so the stabilised tyre pressures measured on the car must be first accounted for in all cases before considering chassis changes. From here forward, we will assume the tyres are operating near their ideal pressure and will not be considered as a set-up option. Having said that, after the set-up of a car evolves significantly, a few runs should be carried out to again confirm the ideal pressure.

Ride height

For a racecar that relies significantly on ground effect aerodynamics, the ride heights will affect the magnitude and front / rear balance of the aerodynamic forces. Aerodynamic effects are discussed separately later. With respect to the 911, ride height affects the kinematic parameters, specifically the roll centre height, but also the c of g. If the front ride height is too high, the front roll centre will be high, and so will the c of g. This will most significantly affect balance, and will shift towards understeer.

Raising the front ride height can be used to improve stability if other changes are exhausted, but it's not the first choice. Conversely, lowering the front ride height improves response to steering.

In the case of the 911, generally the car performs best with the front at the minimum allowed ride height, which also has an aerodynamic effect. The characteristic layout of the 911, however, with the engine position rearward of the drivetrain, results in significant handling variations when set-up changes on the rear of the car are made. Critically, the rear ride height can be raised, which improves corner-entry response, though excessive rear ride height reduces stability both in cornering and hard braking.

Approaching this limit of stability is common practice in racecars with a high polar moment of inertia (and, as such, a high resistance to cornering) by giving the driver the capability to slide the car on the entry phase and have a straighter line on the corner exit. This technique may work for some, but it comes at a risk of spinning and at a cost of tyre life as the higher c of g promotes lateral load transfer with an increase in rear tyre temperature.

Raising the rear also causes an increase in tyre temperature. The disadvantage of this is the higher temperatures produce higher hot tyre pressures, so lower cold pressures must be set. This makes the car difficult to drive when the tyres are cold, and at risk of damaging the tyres by racing on them at low pressure. There is also the additional risk of over pressuring the rear tyres, which can lead to instability and oversteer.

If the car is nervous (unstable) on entry, or the rear tyres are getting too hot, the rear ride height can be lowered. The trade off here is that corner entry response is reduced and the balance shifts towards understeer in the search for more stability.

Anti-roll bar

Anti-roll bars (ARBs, or sway bars) are an additional stiffness element in the suspension added to reduce body roll and for balance tuning. Softening the front ARB will affect balance and shift towards less understeer, but will come with a trade off in response, which will cause the car to be 'lazy' in taking a set in the corner, or during fast changes of direction. So, if the driver is complaining of understeer, it must be determined at which phase during the corner the 'understeer' occurs.

Sometimes stiffening the front ARB can improve turn-in response, especially in high-speed corners. Softening the rear ARB will shift the balance toward more understeer, but with a trade off in stability and response. If the rear axle is too soft in roll, it could take too long to set in a corner and the delay could cause the feeling of sway and lack of body control, This confuses the driver and reduces confidence.

» The stabilised tyre pressures measured on the car must be first accounted for in all cases before considering chassis changes

In addition to the effects on balance, the ARB can also affect grip. Under conditions of low track adhesion (dusty, 'green' or damp surface), stiff settings on the ARBs reduce suspension compliance and one-wheel articulation. This can cause the individual tyres to break traction more easily in low-adhesion conditions. Indeed, on some racecars it is common practice to disconnect the ARBs when the road is wet but, if the track dries during a period where a set-up change is not feasible, the car will then become unstable without the addition roll support. ARB resistance increases with roll angle so, when the chassis is only at low roll angles (corner entry), the relative tuning effect of ARBs is small.

Camber

Tyre construction and the loads on the tyre will determine what inclination each should have with the road for optimum traction.

Ride height plays a major role, especially on aero cars, and an incorrect choice can quickly throw a car's set-up into disarray

Realistically, though, it's difficult to know what that actual inclination is due to compliance in the suspension and the chassis. It's even difficult to control the wheel to achieve ideal camber, but this lack of perfection should not hinder the search for 'good' or at least 'better than the rest.'

A tyre that is inclined with the top towards the car will have two physical outcomes. Firstly, the tyre construction is 'pre-set' in the opposite direction to the lateral load applied to it during a corner. During a corner, the resulting contact patch pressure is more evenly distributed, resulting in better traction and more even wear across the tyre. Despite the likely uneven wear, some tyres actually perform better with relatively high amounts of negative camber (by that I mean more than five degrees), and this is related to the physical tendency of the cambered tyre to turn in the direction of the inclination. This is termed camber thrust. More camber produces more thrust and this results in an increase in corner entry response and increased grip at high lateral accelerations (in the lateral sense).

Increasing camber in the front can affect balance with a shift towards less understeer, though excessive camber beyond the ideal can reduce the contact patch size and traction. Seen mostly in low-grip conditions such as heavy rain or snow, a sudden change from static friction to dynamic friction on the front tyres can lead to the unstable condition, often termed 'plough'. This situation is likened to a motorcycle that falls without recovery when the front tyre loses grip.

Increasing camber in the front also improves response, but at a trade off with traction. In this case, the camber thrust on each tyre is pushing in opposite directions, which can cause a 'tramline' effect when driving on a bumpy road. A small change in steering angle causes the camber thrust to suddenly increase on the outer tyre and decrease on the inner tyre, such that the reaction of the forces results in a turning moment and yaw acceleration in the steered direction.

The more camber a car has, the more thrust and the more response. However, be aware that a racecar that is *nearly* unstable may become unstable with excessive front camber. As a result, front camber can be reduced to improve stability, but at the trade off with response and balance shift towards understeer.

Increasing rear camber, meanwhile, can reduce stability during braking as the contact patch pressure is unevenly distributed, whilst a contact patch pressure concentrated on the outer shoulder of the tyre during a corner can shift balance towards oversteer and, in extreme cases, reduce stability if the contact patch gives way suddenly.

In all cases, increasing camber concentrates the contact patch pressure towards the inner shoulder when rolling straight ahead, reducing the available traction for braking. As a result, increasing camber reduces braking efficiency and can cause tyre lock up or early ABS activation. A second order effect is that reduced braking acceleration lessens the load transfer to the front axle during corner entry, reducing response and possibly shifting the balance to understeer.

Toe in and toe out

By far the most sensitive set-up adjustment is toe, as very small changes can have significant outcomes. More toe in at the front affects balance with a shift towards understeer at a trade off with response. Toe out on the front creates an instant Ackermann effect during turn in (where the inside wheel is steered more than the outside wheel). This improves response, but at a trade off with stability and a balance shift towards oversteer if the Ackerman effect remains dominant in the mid-corner phase.

To improve stability, reducing front toe out could help if other options are exhausted. More effective in improving stability is rear toe. More toe in at the rear will improve stability, but at the trade off with response and balance, and a shift towards understeer. Excessive toe in (or toe out) can increase tyre temperature by producing more scrub, at a trade off in forward acceleration and tyre wear.

Brake balance

In simple terms, when the car is at the balanced limit during braking, all four tyre contact patches experience a small amount of slip, and each tyre is close to locking up. Adjusting the brake bias to the rear would

» Increasing camber reduces braking efficiency and can cause tyre lock up or early ABS activation

shift more braking torque to the rear brakes. This results in the rear tyres on the limit of braking (and traction), while giving the front tyres more tractive capacity to turn. With the rear tyres occupied with braking at the limit, they will slide laterally more easily when induced by the front, improving turn-in response. Therefore, adjusting the bias rearward improves response but at a trade off with stability. Adjusting the bias forward, on the other hand, so the front tyres are at the limit improves stability but can reduce response and possibly induce a balance shift towards understeer during corners with deep trail braking.

Spring rate

In Porsche Carrera Cup, the spring rates are fixed and cannot be used as a tuning tool. However, for completeness, it's important to include them in the discussion. Without going into too much detail, spring rates are selected based on the available grip and amount of body / platform control required for cars reliant on aerodynamic forces. Generally, softer spring rates produce more compliance and more grip in low-adhesion environments, but at a cost to response.

The relative stiffness of the front compared to the rear provided by the springs with the chassis in roll can affect balance, with a shift towards less understeer

Aside from the calculations, it is imperative to measure the car correctly, and for this there is always the reliable red string

Case study

Before anything else, tyre pressures should be checked as they have a direct effect on many other set-up parameters

Now we have a basic relationship of this car set-up to the handling categories, we can consider the VHM in a case study. Imagine the following situation: the car is a 911 GT3 Cup at a high quality European circuit with the set-up described in **table 1** on p87, except the rear ride height is +10mm (10mm above minimum allowed), front is at minimum and the wing is in position four.

During the practice session, using a good set of used tyres on target with pressure, the driver complains the car cannot get to the apex on the corners while trail braking and becomes unstable at the rear on corner exit. This doesn't happen for corners that don't require braking.

In fast corners the car can be placed well but the driver feels that as the tyres degrade the car may become nervous. Braking is very good, but the driver doesn't want to lose that braking performance because it may be needed to defend a position in the race if the car's cornering is not improved.

The starting point here then is to determine how much time we have to make changes. In this circumstance, we have overnight before qualifying the next day. Review of the onboard footage and data confirms the driver's comments, and helps us interpret that the car under rotates on corner entry and trail braking was making it worse (not actually understeer, but lack of response on entry). And that the instability on exit is induced when the driver gets on the throttle, but the slide can be controlled by the driver with no threat of a sudden snap into a spin (not actually unstable, but oversteer leading to loss of drive traction).

The data shows large steering movements in high-speed corners, so the car is over responsive at high speed. Braking is effective, but the front wheels tend to lock up as steering input is increased. The driver is hesitant to brake later for fear of not making the turn, but there's no perception of any wheels locking.

The strengths, therefore, are stability under braking and corner entry, while the weaknesses are over responsive in fast corners, oversteer balance in low-speed corners and a subsequent loss of traction.

We can reduce response in high-speed corners with more wing or lower rear ride height. Wing will only affect high-speed corners and high-speed braking, so we can increase one position. Lower rear ride height will also reduce oversteer balance in the slow corner exits, but will also reduce response on corner entry. We can shift brake bias rearward to reduce front brakes locking, which will reduce stability under braking but increase response on corner entry.

We would also carefully consider adding some more camber at the front to improve response, but with the current trends of front brakes locking up, it's a set-up option to trial after we test the brake bias shift.

At that point, we have suggested several changes, but have also considered their individual effects on the four handling categories. We take the time to explain the trade offs to the driver and get approval to implement the changes. However, there is still time before we need to make the changes, so it's worth considering additional adjustments that could be made mid-session, in case our suggestions end up more, or less, effective than expected.

Our options in pit lane are to soften, or stiffen, the ARBs to shift balance and improve response and to increase, or decrease, rear camber quickly without requiring toe correction, so we can adjust balance and improve rear lateral support (less oversteer) by adding more camber to the rear.

The regulations do not allow ride height changes during qualifying, so perhaps only make a small reduction in rear ride height before qualifying and consider a bigger change for the subsequent races if the change proves effective. Wing position is quick to change in pit lane if the car is losing too much top speed.

Finally, if the track has lots of grip and the car needs more support, we can improve response by stiffening front and rear ARBs simultaneously.

for softer front springs. However, if the spring rates are significantly incorrect for the conditions, the car will become less stable, either through a lack of control of load transfer (too soft) or from poor compliance with the road (too hard).

Aerodynamics

In the context of the VHM, aerodynamics is considered principally with the resulting forces at the contact patches, rather than the forces on the body. In that case, increasing downforce increases grip, but the trade off needs attention. If the increase in vertical load is more on the front axle, the car will see a shift in balance to less understeer, while an excess amount will increase response on turn in and even make the car less stable. If the increase in load is more on the rear axle, the car will gain stability, but the response will reduce. Excessive downforce without sufficient vertical support from the suspension could cause grounding, and damage to the chassis or sudden changes in downforce that would make the car unstable.

As noted in the case study above, increasing front wing angle will improve response at a trade off with stability and a shift to oversteer balance. Increasing rear wing angle will improve stability at a trade off with response and balance.

Conclusion

The Vehicle Handling Model is a tool to visualise the four handling categories, and serves to remind us that optimum handling can be achieved through trading the car's strengths to improve its weaknesses. We assign priority to stability and response before balance and grip, to ensure the driver has confidence and control in order to push the car to its limit. Balance and grip can then be subsequently optimised.

Whilst the process is simple, the key to making effective changes is to learn the car and how it responds to the set-up changes. You don't need a degree or simulation software to do this, you just need to approach your test days with an open mind and a run plan focussed on learning the car, rather than simply searching for the fastest lap. You will then have the information required, and can implement a process to make effective set-up decisions with confidence.

Batteries not included

The complex logistics of transporting electric racing around the globe

By SAM SMITH

Moving electric and hybrid racecars around the world is one thing, moving the batteries that power them has proved quite another

When Jean Eric Vergne hit the wall at turn three in qualifying for the Formula E race, the Diriyah EPrix at Riyadh in November 2019, it took almost a year to move his damaged battery from Saudi Arabia to California to be repaired.

The reason was because no airline was prepared to put a damaged battery in one of its aeroplanes. As a result, engineers from McLaren Applied had to travel to where the battery was stored in Saudi Arabia and work on it in the summer of 2020 for it then to be deemed safe enough to be allowed to fly to Atieva's base near San Francisco.

Flying and shipping hybrid and electric racecars, and the infrastructure that comes with them, adds headaches to the already complex world of motorsport logistics.

For Formula E between 2014 and 2018, this included at least 40 cars with electric powertrains and lithium-ion batteries. It meant the series' logistics team had to learn a myriad certification and health and safety protocols.

While that continues today, it is much reduced in terms of absolute hardware. When the Gen 2 era of Formula E kicked in for the 2018 / '19 season, the field was immediately halved as two cars per driver became just a single Dallara-designed, Spark Racing Technologies-managed chassis, together with a single Atieva-designed and McLaren Applied-supplied RESS (Rechargeable Energy Storage System) per entrant.

Paper trail

Yet plainly, with the cars travelling inclusive of their batteries, it means Formula E's logistics has to make sure all the regulations for the Civil Aviation Authorities (CAA) are complied with. This includes a colossal amount of documentation submitted to the airlines showing exactly what is being freighted.

The precise make up of a battery must comply with criteria issued via the International Air Transport Association (IATA) Dangerous Goods Regulations and details classification flowcharts for specific battery chemistries and products.

The spec Formula E batteries then travel under a specific UN number that allows the batteries to travel inside the cars. This is crucial because the Formula E Gen 2 battery design uses a different cell technology and construction and is located inside the monocoque of the Formula E chassis. It has a greater number of cylindrical battery cells and uses a higher voltage for faster charging and less degradation over a race distance and, as it can travel inside the car, is, relatively speaking, easier to transport.

The main difference between the cells used in the Gen 1 and Gen 2 batteries is the former were pouch designs from Zolt, while the latter is more like the classic AA battery design, sealed in a safety casing supplied by Dallara.

Something called bursts discs are part of the inherent safety system with the Formula E battery. These are sited underneath the battery and act as cushions to dissipate pressure and allow the battery to vent in the event of a sudden abnormal rise in pressure within the battery, negating any explosion.

Within the carbon fibre casing is a deliberate weak point that, should a battery experience a thermal runaway (battery fire) situation, will fail by design, rather than act like a bomb as it might were it to be fully enclosed.

The best way of discharging a Formula E battery is by throwing it into salt water, but clearly that's not a practical solution. So, in the event of a fire, the original plan was for a fire extinguisher to be plugged onto ports built into the engine cover. As the battery case is not tightly sealed, it would allow a slow flow of water through it. These fire ports are designed to feed a constant flow, which would ultimately fill the battery right up with water as the unit has a natural high point.

Dangerous goods

Spare batteries also have to travel but, unlike the ones housed in the cars, these fall into another category for transportation.

'We have to get another certification, called an A99, for these from the airlines for travelling dangerous goods, which is quite difficult in these present times,' says Formula E's head of technical operations, Barry Mortimer, referring to the global pandemic of 2020 / '21. 'The airlines are very demanding. I guess it's not just us, though, but transportation in general.

'There are only a handful of airlines that will actually allow us to travel with these batteries outside what they're supposed to be connected to.'

» The precise make up of a battery must comply with strict criteria issued via the International Air Transport Association (IATA) Dangerous Goods Regulations

DHL, a division of German Deutsche Post, has been Formula E's official logistics partner since the championship started in 2014

» *Racecar Engineering* believes a figure around the $19/20 per kg mark [for air freight] is reasonably accurate as it stands

Mortimer and his team work closely with the Formula E teams and manufacturers on solutions to these problems. As an example: 'We're just working on a procedure where we can fit the spare batteries into the spare chassis,' details Mortimer. 'That will then be classed as the batteries travelling within the car and what it's connected to, so then we can move on from the A99.

'The civil aviation authorities are making it incredibly difficult for us with those regulations at the minute though.'

Mortimer is also working closely with DHL, the official championship logistics partner since its inception in 2014, and is almost on hour-to-hour levels of communication at present.

'I think there may be a lack of knowledge from the airlines side sometimes, a lack of technical knowledge that is, so they need to speak to the manufacturers and the manufacturers need to link up with the airlines and explain specifically the safety procedures we have inside the batteries,' continues Mortimer.

To make matters worse, the regulations for transporting batteries on airlines change by the year, and seem to be making it more and more difficult for Formula E in particular.

Consequently, the series has used alternative transportation methods and prides itself in its sustainable approach to operating. In 2020, it became the first sport series to have a net zero carbon footprint, using and developing internationally certified projects in its markets to offset emissions from its racing.

Express train

In its second season, it transported its cars and freight on the trans-Siberian express train to Beijing and sent its freight from 2021's double-header race in Puebla, Mexico to the following encounter in New York City via road haulage.

But sea freight, road and other alternatives are generally less flexible than flying, especially in an uncertain world where calendars have had to chop and change, as with Formula E since the start of 2020. Additionally, the over-arching disruption to the travel industry, and by proxy the logistical needs of major live sporting championships, means compromises have had to be found quickly.

Then there is the cost factor, which is not actually as different to regular motorsport freight plans as many believe it is.

'I don't think electric racing is any more expensive really than, say, Formula 1, because we still need to fly a certain amount of goods around in our freight,' says Mortimer. 'I've been gifted the huge project of reducing our air freight to an absolute minimum going into season nine [Gen 3], reducing it to flying just the absolute race-critical things.'

Two 747s are used for many of the Formula E events, usually across five continents. The costs are not in the public domain, and Mortimer wouldn't be pushed on specifics, but *Racecar Engineering* believes a figure around the $19/20 per kg mark is reasonably accurate as it stands.

Going back to the sea freight possibilities, costs have escalated dramatically there in pandemic times, making it a much less desirable option on a commercial basis, with an additional level of uncertainty to boot.

'If we go back maybe five years, you would say sea freight was around a third of the cost of air freight, but now the prices have risen astronomically,' confirms Mortimer.

'I wouldn't say it was as expensive as air freight, but they're not that far away from each other now. Though obviously, sending things with sea freight is more sustainable and a lot more economical than by air.

'This is what we're pushing even harder for 2022 / '23, to try and take an absolute minimum by air and then the rest via sea freighting. So that's potentially just the cars by air freight, and that's the big project we're currently working on.'

Radio rental

As you might expect, it isn't just the batteries in the cars that must be certificated and almost forensically detailed for transportation, there's the communications network to consider as well.

'We carry about 48 radios, something like that,' notes DS Techeetah's team manager, Nigel Beresford. 'Each one of those has a battery that is individually packaged and kept separate, and also certificated. There's an enormous amount of paperwork associated with the freight and additional detail now required.

'This is in terms of harmonised codes to characterise what each item in the freight is, what it's made of, what colour it is, what the serial number is etc. And that's for the thousands of items we carry around that are not actually in the car itself.

'That is how come you end up employing someone specifically to look after the logistics aspect,' adds Beresford.

DHL has shared a focus on innovation and sustainability with Formula E since 2014. In 2017, under its 'Mission 2050' strategy, Deutsche Post DHL Group set itself the goal of reducing logistics-related emissions to zero by 2050.

Electromobility is a vital part of that strategy and Deutsche Post DHL Group is a pioneer in the area of green logistics, particularly with its Street Scooter, a selfdeveloped electric delivery vehicle that has been deployed thousands of times in Germany and Europe and is also sold to third parties. The company also boasts a fleet of over 11,000 electric vehicles worldwide.

Pioneering spirit

'As an action-packed and, at the same time, green racing series, Formula E is synonymous with the combination of innovation, future viability and sustainability in motorsport, in the same way that Deutsche Post DHL is in the field of logistics,' says DHL's head of brand marketing, Arjan Sissing.

'The technical developments being advanced in Formula E in the area of electromobility are often significant because the racing series serves as a platform for testing new technologies.

'Other sectors, including the transport and logistics industry, are also benefiting from this pioneering spirit.'

For Formula E, the physical strength of its many containers is clearly crucial to appeasing the stringent protocols put in place by airlines. The freight boxes themselves have to go through vigorous safety testing and have to pass certain certifications. They must be effectively bombproof for, as with the cells inside the batteries, the potential for a thermal runaway scenario is always there.

This occurs when the heat generated within a device exceeds the amount of heat it is capable of dissipating to its surroundings.

In terms of a battery, if the internal temperature continues to rise, the battery current also rises, leading to a domino effect that is almost impossible to quell. The result would, obviously, be catastrophic on any transportation vessel.

'There is nothing you can do with it and you just have to let it run out by itself,' notes Mortimer. 'And all of that is encased within these freight boxes.'

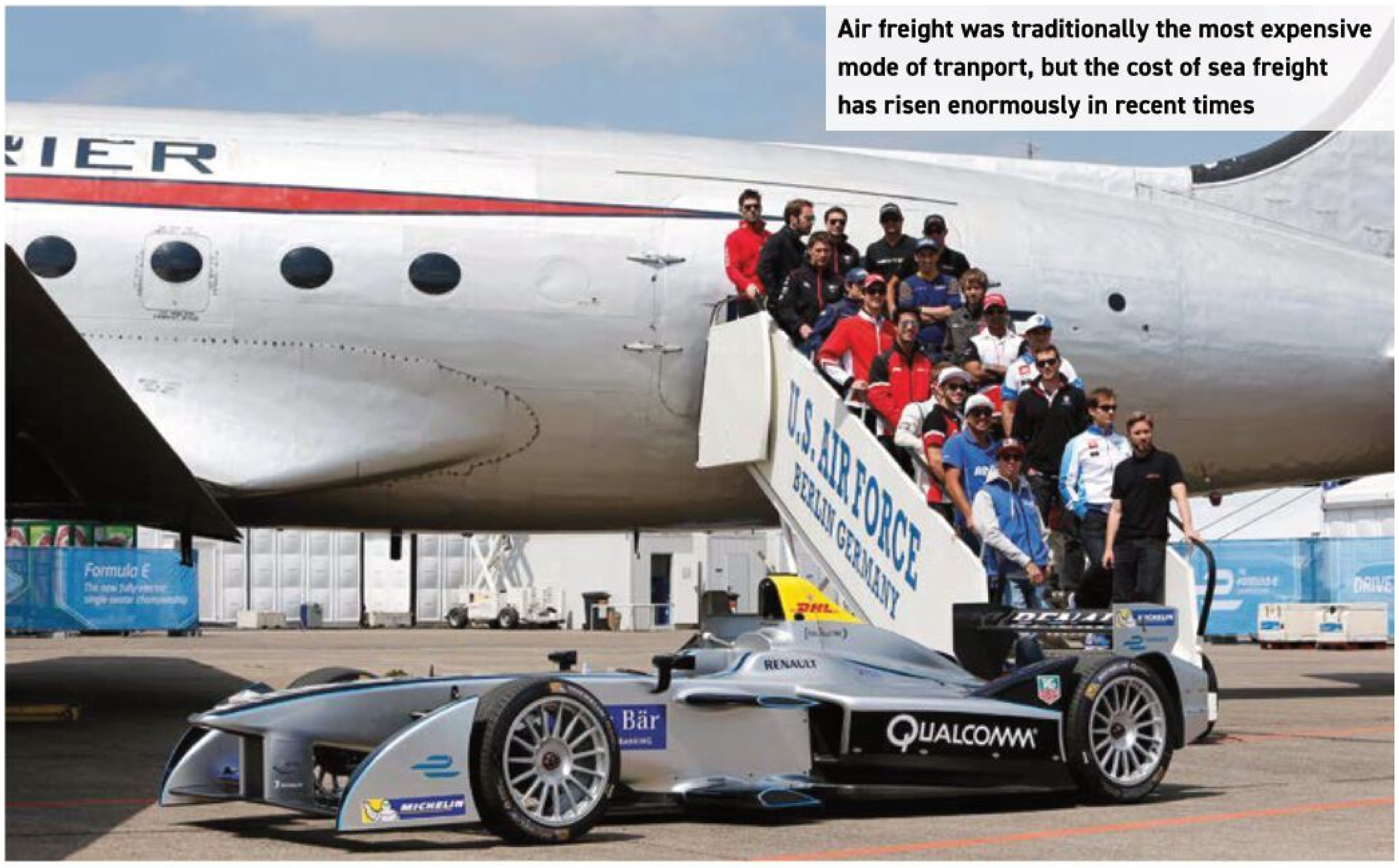
Background noise

There's more to motorsport logistics than just moving batteries and cars around of course, and, having joined Formula E in his current role in 2019 after a variety of sporting and technical positions at Virgin Racing and NIO, Mortimer is in a good position to say that seeing how it works from the other side of the fence is 'a big eye opener'.

'Previously, I worked on the teams' side of things, and coming in on the championship's side you see it from a different perspective. You don't realise what goes on in the background to put on these events.

'It's just incredible. The way we've reacted to Covid, and how we've grouped together to put the events on is, I believe, unprecedented.'

Which brings us to another whole level of logistics that simply didn't exist before the Covid 19 pandemic.



Air freight was traditionally the most expensive mode of tranport, but the cost of sea freight has risen enormously in recent times

'The first thing we did was partner up with a health company. We do our own PCR testing on site, and just the logistics of that is immense.'

Mortimer has also overseen the moving of all the PCR equipment since the beginning of the pandemic, including the complex, temperature-controlled kit required to look after the medical pods, testing fluids etc.

The specially constructed boxes for this testing and tracking equipment to travel in has mimicked the attention to detail seen within a professional racing team.

'I'm used to managing teams to a minute-by-minute schedule from when we arrive at the circuit to when you leave,' he notes, 'but seeing it now from the Formula E side, the management behind all of the championship is just huge. You've got everybody gelling to bring these events together and make them happen.

'The background I've had has certainly helped because I've been involved with Formula E since the beginning.'

The team Mortimer manages is away for 15 days per event, which includes waiting for the freight to arrive, delivering all the myriad parts to their specific places and then prepping everything for the teams' arrival.

Straight lines

Placing equipment where needs to be requires accrate marking on the paddock floor before freight is unloaded from the sea freight containers. When it is then placed by forklifts in the paddock, the lines are perfectly straight with the same gaps between them. It takes a certain type of mind to be able to visualise that in 3D from an empty space.

'Everything has to go in its correct place, including things like the Emotion Club [Formula E's mobile VIP centre] and building up the TV compounds.' The latter is a key part of the logistical effort for the all-electric championship as the TV compound on its own is made up from 11 specially made pods.

» Other sectors, including the transport and logistics industry, are also benefiting from [Formula E's] pioneering spirit

Barry Mortimer, head of technical operations at Formula E

'That's why we're working really hard now to bring all of that air freight down to the absolute bare minimum,' continues Mortimer. 'We've been flying around the world for the last six seasons using 747s. For season nine, we're going to the 777.

'That alone is a massive project. The 777 is a lot smaller, but it's more economical and can take the same payload. That's why we're working with the teams now to see how we are going to package everything for 2022 / '23 onwards.'

The sheer scale of safety protocols in moving electrically-engineered hardware around the world is one of the hidden challenges of modern motorsport, and one that is only going to grow in the future.

With the added challenge of a world still dealing with the effects of the Covid pandemic at the tail end of the 2021 calendar year, and the inevitable slow return to something approaching normality, those challenges now have to be met head on by the likes of Formula E and the host of new EV series, including Electric GT, Pure TCR and Electric Rallycross – pioneers all of a new way of thinking. ●

Making tracks

Achieving close racing in the World RX Championship is not just about equalising car performance. Clever track design can be the difference between entertainment and boredom

When a circuit requires jumps, asphalt *and* loose surfaces, the design challenge becomes a lot more complicated. *Racecar* speaks to the experts about the science behind the creation of World Rallycross tracks

By GEMMA HATTON

The combination of circuit racing, rallying and drag racing that is World Rallycross (RX) is fantastically entertaining. Add to that the technical challenges of setting up a car for both asphalt and dirt surfaces, while coping with the impact of jumps, and acceleration times faster than F1, and it is, for many, the perfect balance between engineering and entertainment.

World RX is also arguably one of the fastest growing category of motorsport in the world, and with growth comes expansion. In 2017, the World Rallycross Championship concluded in South Africa for the first time, while 2018 saw the introduction of two new venues – Silverstone in the UK, and COTA in the USA while others including Spa have joined since.

'There are two or three other territories that we are talking to seriously as well as a few additional European ones, but we don't want to go to a 16-round calendar,' said Paul Bellamy, managing director of FIA World Rallycross and global head of IMG Motorsports. 'We've talked to nine promoters in China. Then there is the Middle East, and there's an opportunity in South America, but it is about balancing the new rounds with those we have already got.'

So with new venues popping up each year, and more on the horizon, how do you go about designing these unique rally cross tracks? Where should the 'Joker' lap be? How do you manage the behaviour of the dirt surface for driveability? As ever in engineering, there is a lot more to this than meets the eye.

'Historically, Rallycross tracks were built by stripping off the layer of topsoil and then they would go racing,' explains Dafydd Broom, design director at Apex Circuit Design, which was behind the development of the Barcelona, Bikernieki

» The demands of World Rallycross has led to the development of unsealed surface materials to cater for this international series

» Although it may seem part of the challenge for the driver, poor surface durability actually poses an operational challenge and risk

(Latvia), Hockenheim and Cape Town World RX tracks. 'However, the demands of modern Rallycross has led to the development of unsealed surface materials to cater for this international and highly commercial series.'

When Apex first began working with IMG to develop these new RX tracks, it was asked to supplement the FIA guidelines with additional IMG self-imposed standards that aimed to address issues such as jump design, track limits, venue branding and circuit presentation.

Loose talk

One of the primary review points was the specification of the unsealed surface. As specified by the FIA, 60 per cent of each RX track must be a sealed surface with the other 40 per cent an unsealed surface. Whilst the sealed surface is commonly asphalt, the unsealed has taken many forms over the years resulting in varying degrees of performance, and it was this variance that IMG wanted to address.

'The first key performance specification was with regard to surface durability,' Broom says. 'Often the unsealed surface of the track can rut which is where the loose material ends up creating channels in the track which the tyres slip into and this can generate an uneven surface and is horrible to drive on. The RX supercars are very powerful, they generate 600bhp and have the ability to accelerate from 0-60mph in less than two seconds. This performance results in a large load being put through the surface of the track that can cause increased wear, especially for the unsealed surface, that often manifests itself in rutting.'

Although this may seem part of the driver challenge, poor surface durability poses an operational challenge and risk. With more than 80 races across a single weekend, the track needs to remain consistent with as little maintenance between races as possible.

'The second performance specification centred around presentation and safety,' says Broom. 'Unsealed materials up until now have traditionally been quite loose and, when wet, very dirty. This can result in material being swept up by the vehicles and then projected behind causing drivers in their wake to lose visibility or even damage their cars, whilst posing a potential risk to spectators in close proximity to the track, and poor presentation of the series vehicles and sponsors.'

Therefore, a new unsealed surface specification was developed for the sport that not only met all of IMG's criteria, but also allowed for a variance across the series due to the different constructions required to suit the varying ground conditions around the world.

Solid ground

Essentially, the modern specification for the unsealed surface is one that utilises soil stabilisation techniques that result in a surface that is as hard as concrete, without being classified as a sealed surface.

The first stage of building a track is to conduct a geotechnical investigation in the proposed location to understand the properties of the material found on site and to understand what sort of stabilisation technique would be most appropriate to those specific ground conditions.

'For example, if it is a clay-based material, we can mix it with varying degrees of lime to create a hard surface so it becomes a very stable material,' says Broom. 'When we don't have that clay-based material we can make use of a concrete binder to create that hard surface with the even and consistent wear that you see on modern circuits.'

With every passing racecar, the surface slowly and evenly deteriorates, generating a fine loose material that settles on the surface and therefore reduces its frictional coefficient, although a light sweeping between races can brush this away before it causes issues.

'Ideally, you need to stabilise the top 25cm of soil so it remains robust, but loose, so that the car feels like it is on a loose

There is an amazing amount of science that goes in to developing the perfect type of dirt for RX cars to race on. The aim is to make a loose but stabilised surface with minimal dust

surface. The trick is how you achieve that whilst minimising any dust that is thrown up,' says Karl O'Sullivan, who helped IMG develop tracks before becoming team manager at GCK World RX Team.

'If built correctly, that 25cm layer of topsoil should last between three to five years. Below that is a sub base, which can consist of a wide variety of additives and binding agents all mixed together. Ultimately, it will depend on the specific properties of that soil and samples will be analysed in a lab to create the unique magic potion that will stabilise that surface correctly.'

To manage dust levels, natural materials such as water or man-made additives such as Dustex, often used in quarries, are sprayed on to the unsealed surface to suppress the dust.

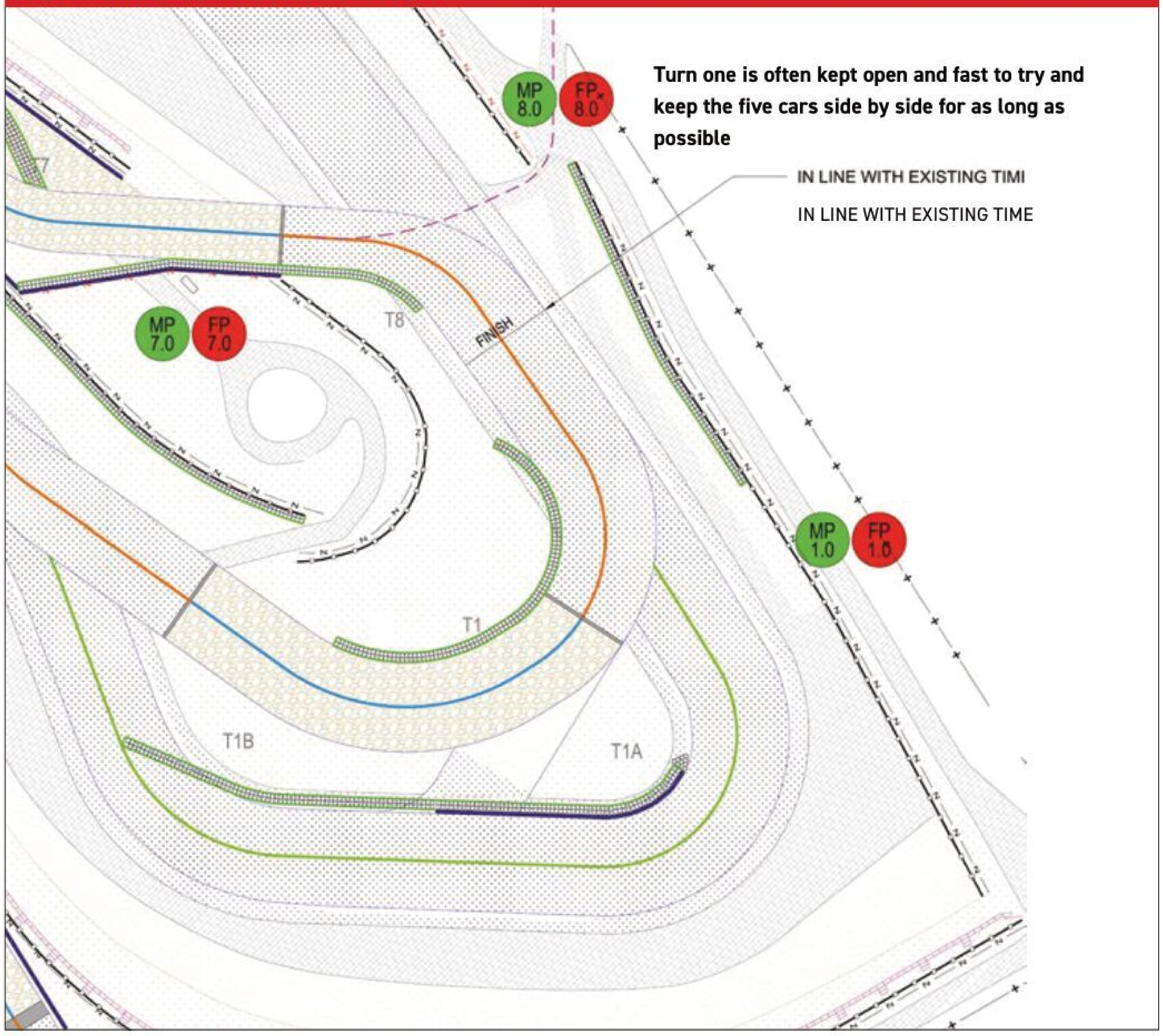
You may think that because the track is hard with low wear, track evolution doesn't exist, but that's not the case.

'Actually, because the material is so hard, the unsealed surface does in fact rubber up,' says Broom. 'So there is a period of time where more rubber gets laid on the track and the rate of this depends on track temperature. For example, the track in COTA that we designed was already rubbering up during the tests, especially through the corners. This will create a constantly changing track dynamic that drivers will have to react to.'

Crossing the tracks

So that is the science behind the surfaces, but what about the layout? As World RX is an FIA championship the governing body has guidelines that track designers have to comply with for their circuit to obtain a racing license. These guidelines specify parameters such as the distance between the start line and the first corner, the width through the first corner and the track width.

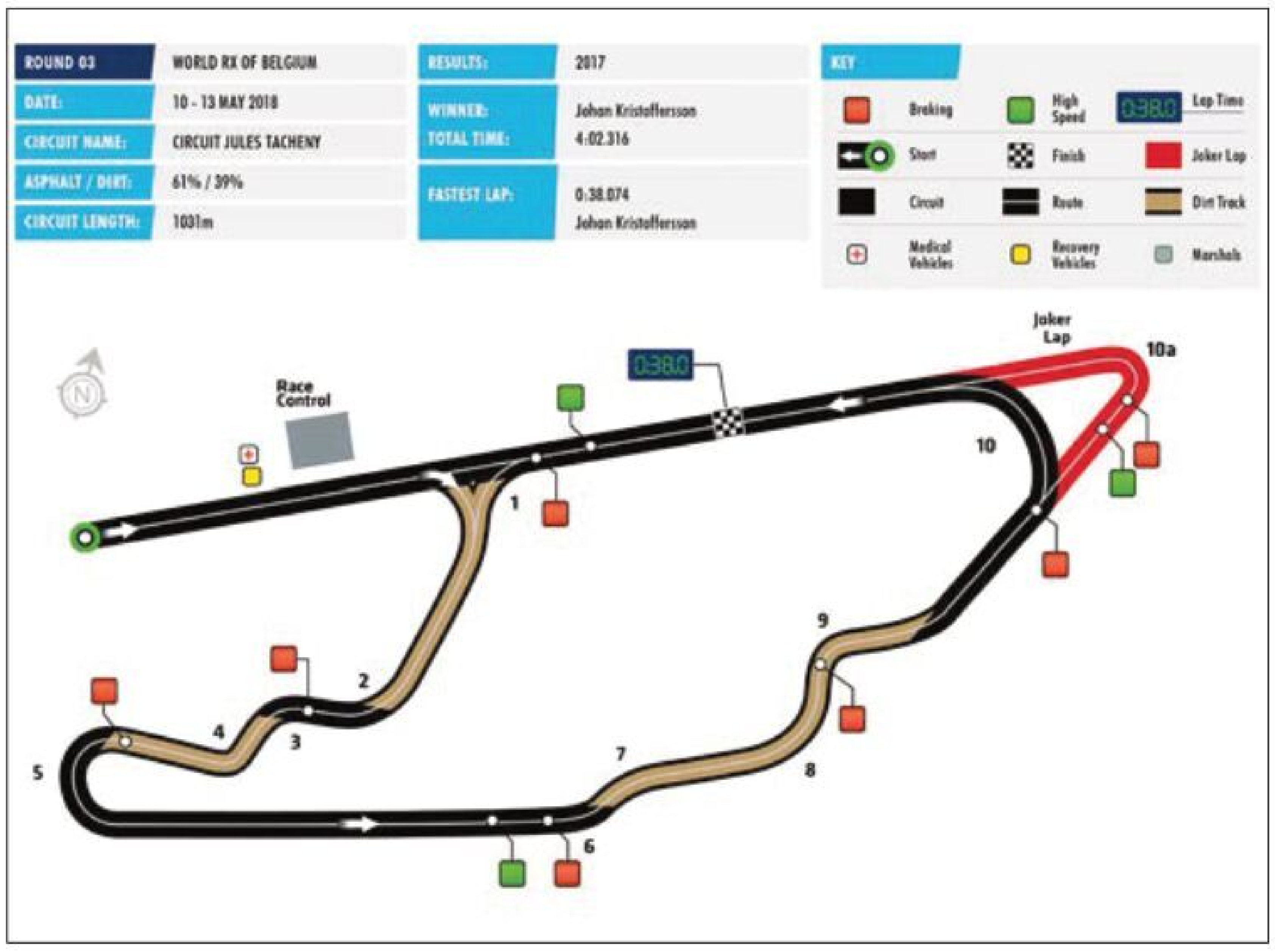
Figure 1: A typical track design

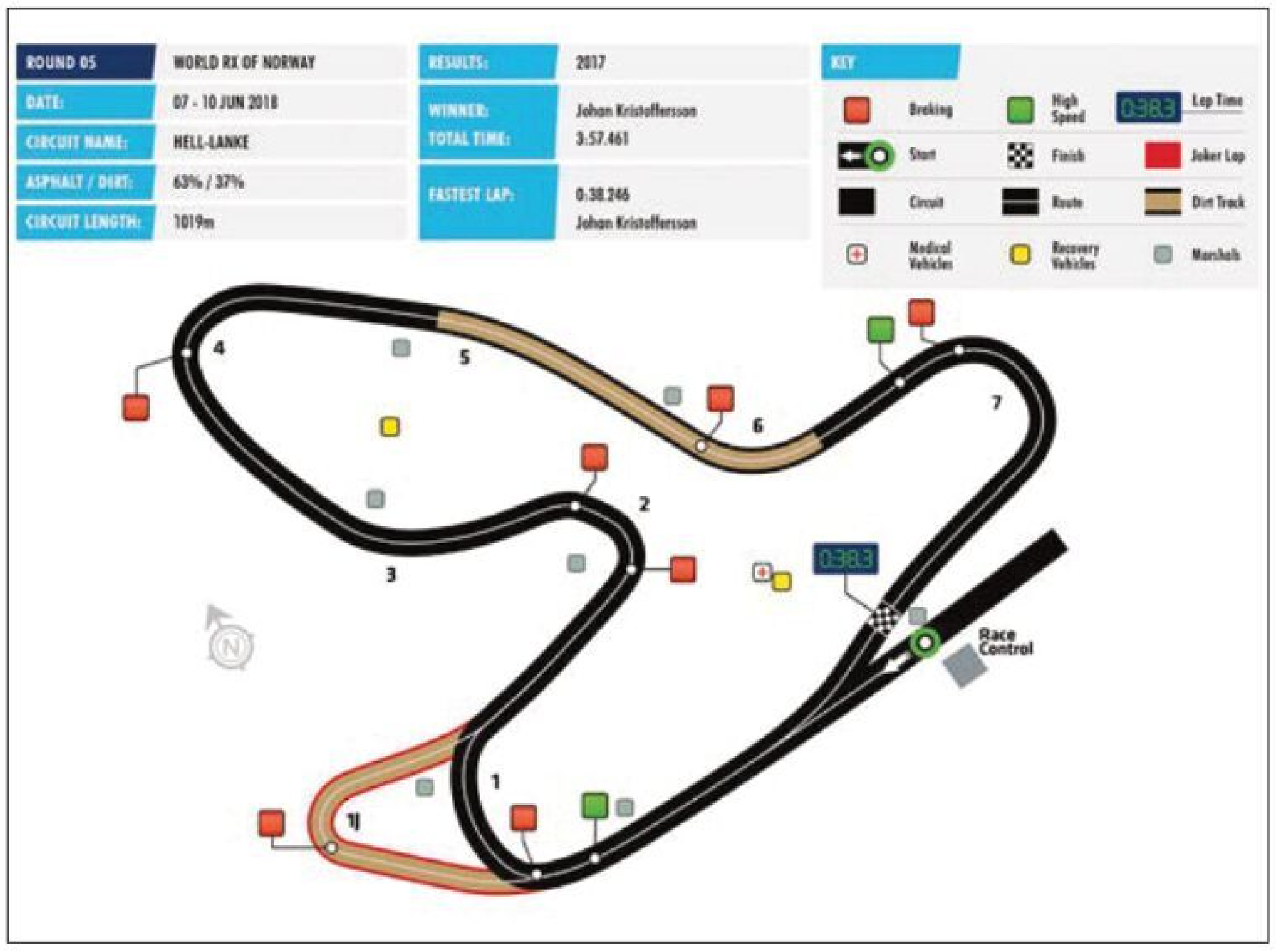


Usually, turn one is kept as open and as fast as possible to try and keep the cars side by side and avoid a single line, as this draws out the cars into single file, which is not ideal for such short races (**Figure 1**). However, in cases like Riga, this could not be achieved as the long straight meant speeds into the first corner would be too high and therefore require a very large run-off area, which was not possible. So, to slow the cars down, a small chicane was added.

And then there are jumps. 'Where you have lots of flexibility is the position of the jumps,' says Broom. 'If you are building a

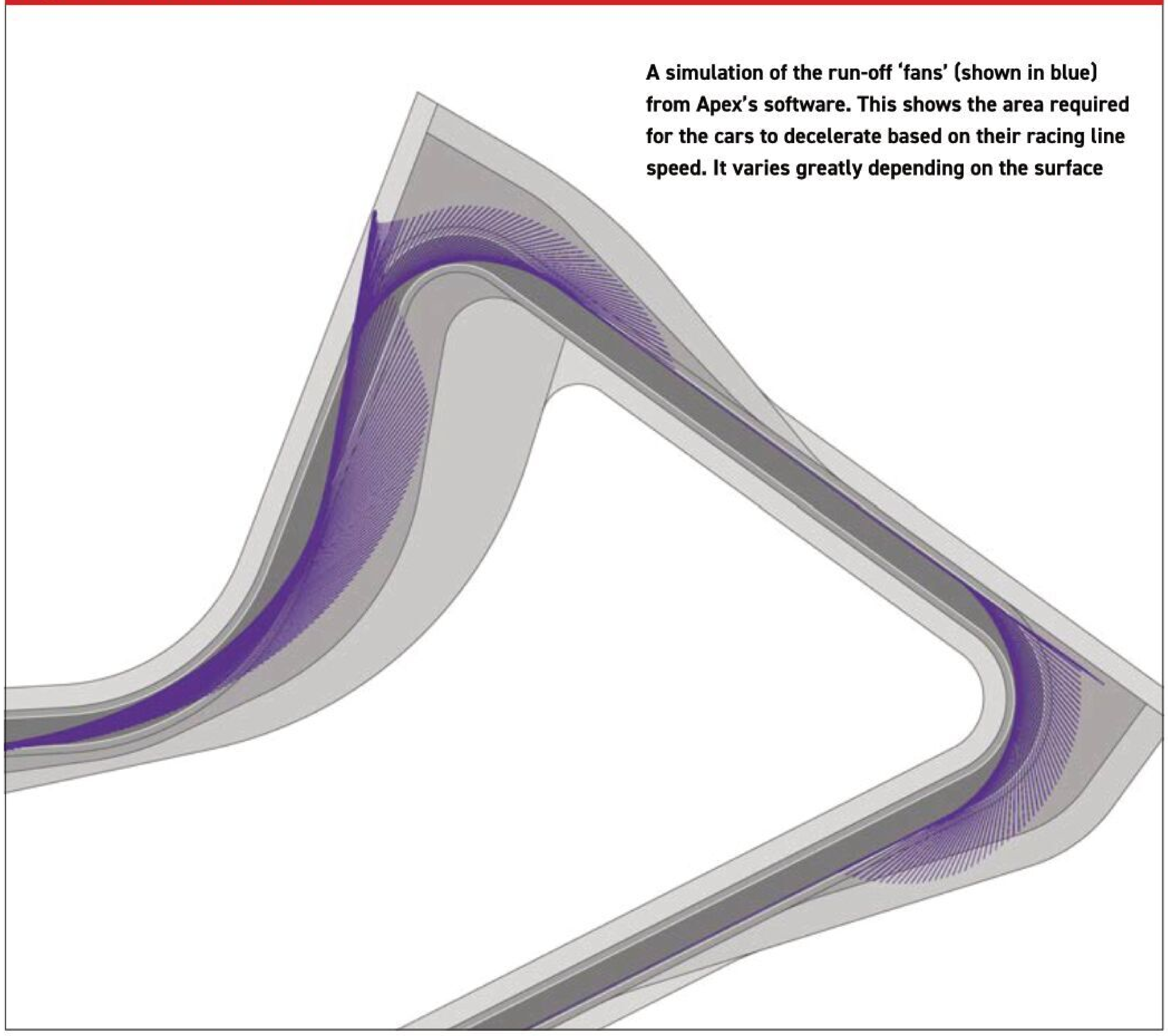
> **» If it is a clay based material we can then mix it with varying degrees of lime to create a hard surface, so it becomes very stable**





The 'Joker' lap is peculiar to World RX. It requires cars to take one longer lap via an extension. Some say that to maximise the excitement this should be towards the end of the lap, such as in Belgium (left), to have cars battling for position across the finish line, rather than how it is in Norway (right) where you can end up with what seems like two different races

Figure 2: Run-off areas



A simulation of the run-off 'fans' (shown in blue) from Apex's software. This shows the area required for the cars to decelerate based on their racing line speed. It varies greatly depending on the surface

green-field track then you would look at the natural elevation changes that already exist to develop jumps that challenge the drivers. However, most tracks are retro-fits to other circuits, so you have to artificially add them in, which limits the geometries and style of jumps you can create.'

New challenges

As IMG continues to grow and improve World RX to become a renowned worldwide form of motorsport, naturally races are held at bigger and better venues. For example, in 2018 the UK round was controversially moved from Lydden Hill to Silverstone because World RX had simply outgrown the historic venue. This adds to the list of challenges that modern RX track designers have to face, because retro-fitting an RX track to the requirements of the overall circuit is no easy task.

» When building a green-field track you would look at the natural elevation changes that already exist to develop the jumps

'When you have to adapt a circuit for RX, you have to be sympathetic towards the Monday-to-Friday operations of that circuit,' says O'Sullivan. 'The challenge is to develop a circuit that feels permanent during the World RX weekends, but is temporary in the eyes of the wider circuit.' This can therefore dictate elements such as the height of jumps or any banking.

Another thing that sets World RX apart is the 'Joker' lap. This is an extended lap every driver has to take once during each race that is designed to add at least one second to the lap time. To achieve the most exciting racing, the Joker layout is usually put close to the end of the lap, so that if drivers choose to take their Joker on the last lap, they come out alongside the others, battling for position as they cross the finish line.

'There are different thoughts on this, but I feel having the Joker towards the end of the lap provides more entertainment,' says O'Sullivan. 'There are a number of circuits where the Joker lap is at turn one, so in a five-car race two can take it while the other three continue around the normal track, so effectively you get two different races. I prefer seeing all five cars racing alongside each other for at least one lap before anyone decides to take their Joker.

'You need to make sure the merge is parallel with the cars on the main track and that everyone is travelling at a reasonable speed so it really does go down to the last corner, which is great from an entertainment perspective.'

To help with the design process, Apex has developed a unique software programme that effectively utilises Matlab code to simulate the safety of its designs, which can then be modified accordingly. Data points from the CAD model of the track are imported into Matlab and real car data is used to define the racing line. This allows the horizontal and longitudinal accelerations and speeds of the vehicle to be determined at each point around the track.

Once these speeds are defined, the software then simulates how long it will take the vehicle to decelerate in the event of an accident, and therefore how long the run-off areas need to be. Run-off areas can either be grass, gravel or asphalt and the FIA has specified guidelines based on tests that define the deceleration rates of a vehicle on each of these types of medium. Asphalt decelerates a car quicker than gravel, while grass takes the longest.

The simulation then generates run-off 'fans' (**Figure 2**) that dictate the dimensions of the run-off areas depending on the selected medium, so the geometry of the track can be tweaked to meet the safety and cost requirements.

'If it's not possible to have the space required for grass run-offs, for example, we change the medium to gravel. If we are still in the barrier, we add more asphalt,' Broom says. 'In some cases, you still won't have the space for the required run-off areas so then you use energy dissipating barriers. Our software is extremely sophisticated and it allows us to simulate designs quickly. So, as soon as a line is put on the plan, we are able to quickly CAD up the track and have a simulation done within 10 minutes.'

Flip side

The vertical geometry of the track is also another consideration. 'You want to try and minimise the opportunity for cars to flip due to aerodynamics, like we have seen at Le Mans in the past. Again, the FIA have put in guidelines to address this issue,' says Broom. 'For new circuit venues, the vertical elevation of the centreline of the track should be proportional to the speed of the car. By working this out, our simulation then gives us the maximum radius we can have for vertical transitions. This is where it is hard to get some of the qualities of classic tracks into modern ones, because classic corners such as the Corkscrew at Laguna Seca are very much outside the current FIA guidelines, which is what makes them so special. We try to push the boundaries and make them as extreme as possible within the rules to improve the driver experience, but obviously safety is paramount.' ●

Stabilising influence

Why incorporating the stability index into your lap time simulations is critical if you're searching for a set-up that's both fast *and* driveable

By DANNY NOWLAN

One of the biggest criticisms levelled at lap time simulation packages is that handling is an afterthought, and that they can even come up with set-ups that are undriveable. I will admit I have fallen into this trap on many occasions, and about two years ago I wrote an article that discussed this in depth. Then, upon re-reading it recently, I saw there were a couple of key themes that should not only be reviewed, but explored in greater depth.

The reason this situation exists is that we in the business have done an appalling job of defining racecar stability, primarily because what drives it is very poorly understood. But the good news is, once we address this, a lot of things fall into place.

So, to kick off this discussion, while refreshing everyone's memory, the stability index (stbi) is the primary driver for understeer and oversteer. It has its origins in aircraft longitudinal dynamics and it's a measure of the moment arm between the centre of gravity and the centre of the tyre forces, as shown in **figure 1**.

The neutral point is the location of the sum of the lateral forces. With the stability index, what we are measuring is the moment arm between the centre of the lateral forces and the centre of gravity. We then non-dimensionalise by dividing it by the wheelbase.

The stability index is such an important measure because of how it varies with the lateral load transfer distribution at the front. Here it is worth reviewing an earlier analysis I did when I discussed the significance of the magic number. This is shown in **table 1**.

To say these figures are fascinating is an understatement. As we can see, the peak lateral force occurs at a front lateral load transfer of 0.5. Not surprisingly the stability index is very marginal at -0.00291. What is interesting is when we go to a lateral load transfer factor of 0.6 we drop only 80N of force, but the stability index drops to -0.072. This is a big change in handling.

What is even more interesting, though, is that the spread of forces is only about 1000N, or about four per cent. However, we see large fluctuations of the stability index. To fully appreciate this it's worth looking at it graphically, and a plot of lateral load transfer *vs* available force is shown in **figure 2**.

For effect, I've put the maximum number of this plot at 25,000N and the minimum at 0N. Note the small variation. But plotting the stability index shows a completely different story, as seen in **figure 3**.

Incidentally, a colleague of mine plotted this out once, and then immediately 'phoned me and said 'you are on to something here and if you don't pursue this you are nuts'. He was right, as **figure 3** is crucial when it comes to driver feedback.

Inherent instability

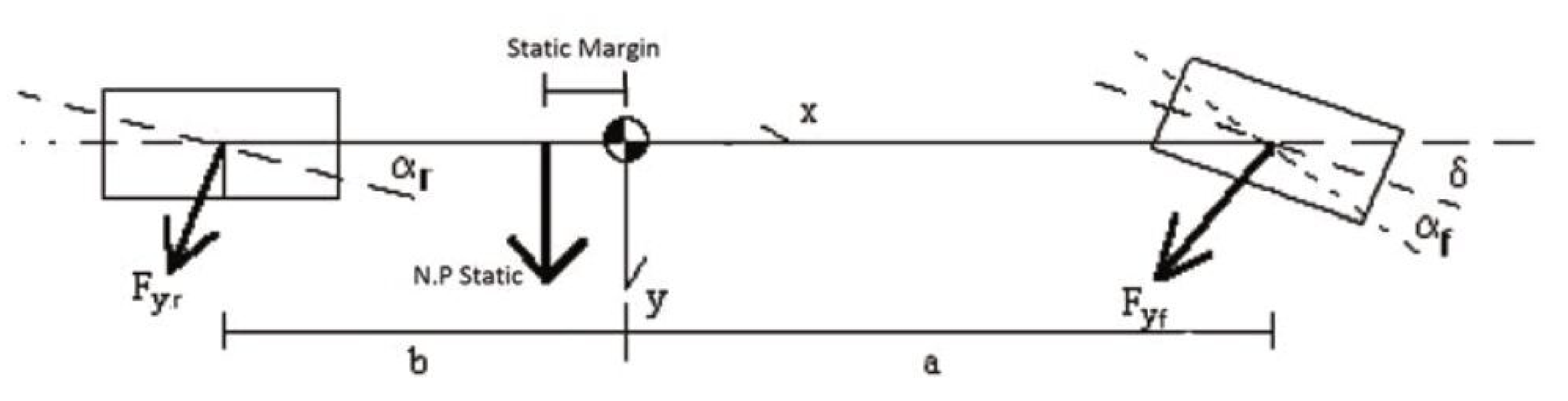
Before we get on to why the stability index is such a good measure of quantifying driveability changes, we should first discuss why lap time simulation will sometimes favour an unstable response. The simple answer is that at times this is where the grip is. For instance, you might remember previous articles on the magic number where we have discussed why the ideal lateral load transfer for a rear-wheel-drive car was 0.473.

Also, remember that one of the biggest advances in fighter aircraft design came

Table 1: Results of lateral load transfer *vs* the stability index for an F3 car

Front lateral load transfer	Total lateral force (N)	Projected front slip angle (deg)	Stability index
0.1	21952.64	4.24	0.162
0.2	22264.4	4.42	0.13
0.3	22479.4	4.6	0.09
0.4	22597.6	4.80	0.05
0.5	22619.05	5.01	-0.00291
0.6	22543	5.24	-0.072
0.7	22371	5.51	-0.166
0.8	22102.6	5.8	-0.303
0.9	21736.9	6.14	-0.524

Figure 1: The stability index



Where:
F_{yf} = total lateral force at the front
F_{yr} = total lateral force at the rear
δ = steer angle
α_f = front slip angle
α_r = rear slip angle
a = moment arm between the front axle and the centre of gravity
b = moment arm between the rear axle and centre of gravity
NP = neutral point

» One of the biggest advances in fighter aircraft design came when the performance potential of making aircraft unstable was recognised

Figure 2: Total lateral force vs front lateral load transfer distribution

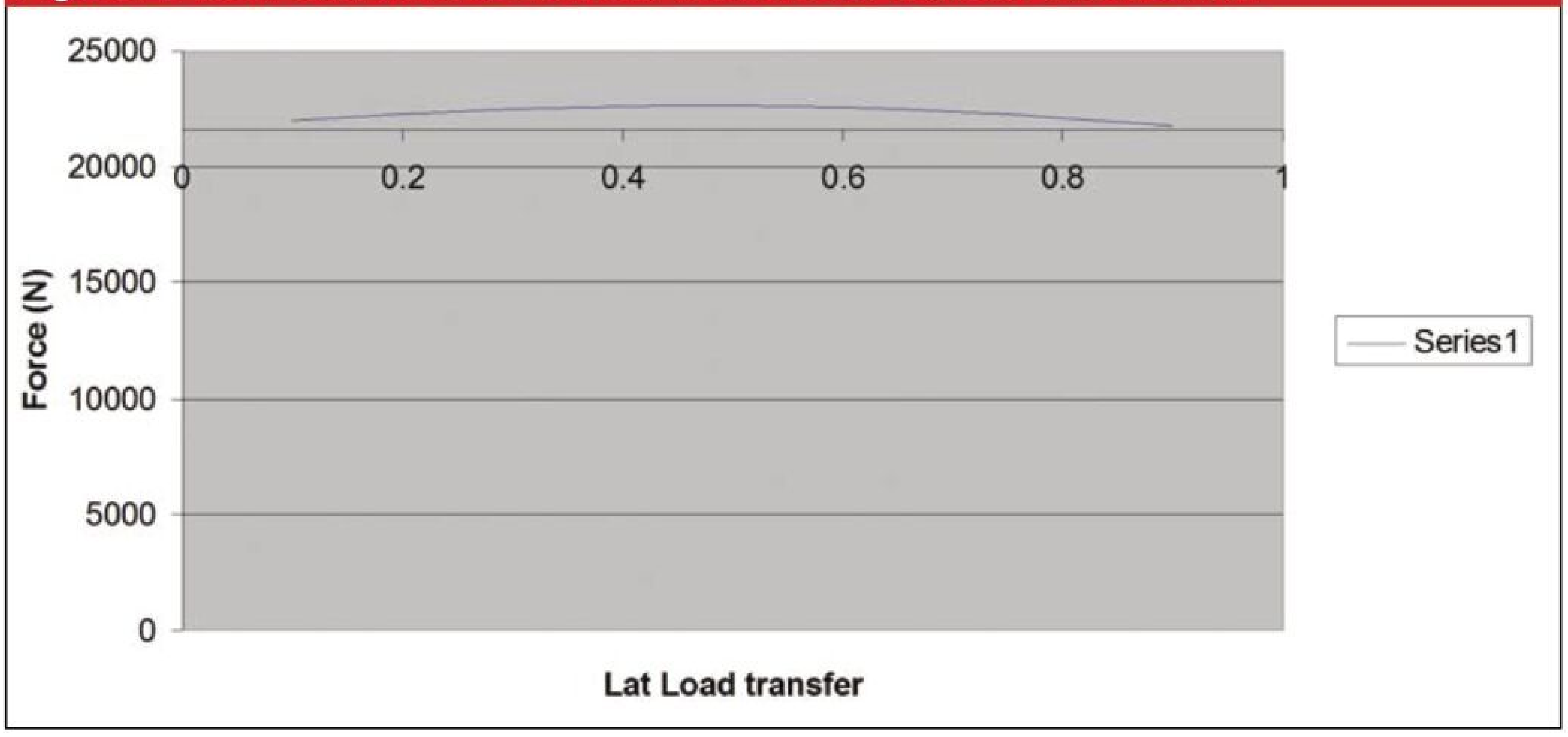
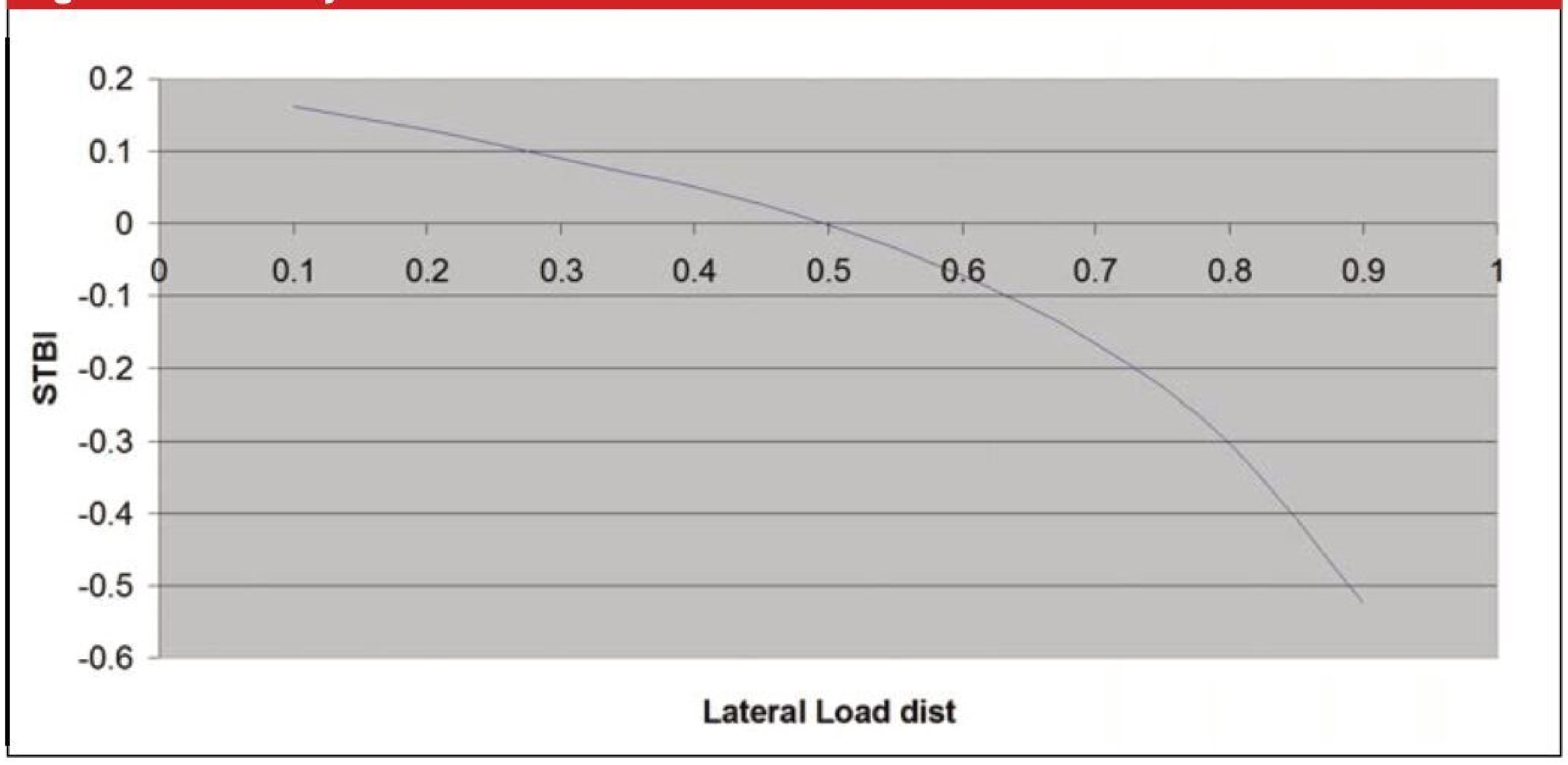


Figure 3: Stability index vs front lateral load transfer distribution



when the performance potential of making aircraft unstable was recognised. This trend was kicked off by the F-16 and has come to full maturity in the extremely agile designs you see with the Russian Sukhoi Su-35S and the Su-57. They are unstable because that is where the performance is, and it is no different to what we have seen with the magic number before.

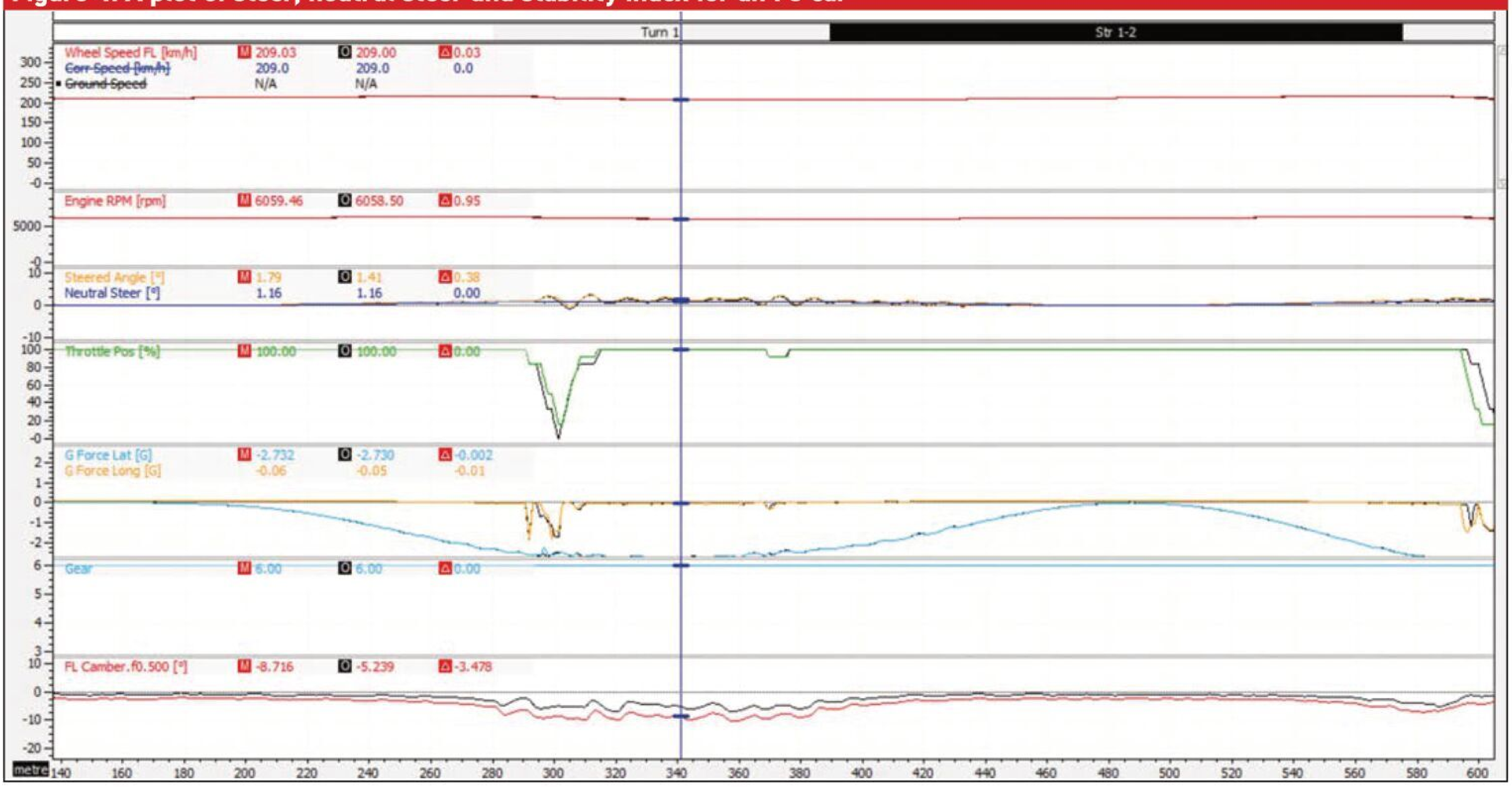
Stability ability

The next question that needs to be addressed is why the stability index is such a good measure of driveability. To answer this, let's compare the simulated results of an F3 car with an aero balance at stock, and then with the aero balance of plus five per cent towards the front axle. This is illustrated in **figure 4**.

If we take a look at the mid-corner condition, there isn't a lot of change in speed and the steering has reduced by 1.8 degrees to 1.4 degrees. However, where things really change is with the stability index, which is the bottom plot, shown as a percentage (ignore the 'FL Camber' title). The baseline has a stability index of -8.76 per cent and the change shows a stability index of -5.3 per cent (the reason this is filtered is because the circuit is bumpy, and ChassisSim can respond at 400Hz. As a rule of thumb a 5Hz filter works really well). Anyone who has spent more than five minutes in F3 will know this is a change even the most inexperienced driver will feel.

» **Anyone who has spent more than five minutes in F3 will know this is a change even the most inexperienced driver will feel**

Figure 4: A plot of steer, neutral steer and stability index for an F3 car



The reason why this is such a clear measure of driveability change lies in the mathematics. The formula for the stability index is shown in **equation 1**, below.

$$
\begin{aligned}
C_f &= \frac{\partial C_f}{\partial \alpha_f}\Big|_{\alpha=\alpha_f} \cdot (F_{m1} + F_{m2}) \\
C_r &= \frac{\partial C_r}{\partial \alpha_r}\Big|_{\alpha=\alpha_r} \cdot (F_{m3} + F_{m4}) \\
C_T &= C_f + C_r \\
stbi &\approx \frac{a \cdot C_f - b \cdot C_r}{C_T \cdot wb}
\end{aligned}
\qquad (1)
$$

Where,

$\delta C_f / \delta\alpha(\alpha_f)$ = Slope of normalised slip angle function for the front tyre
$\delta C_r / \delta\alpha(\alpha_f)$ = Slope of normalised slip angle function for the rear tyre
$F_m(L_1)$ = Traction circle radius for the left front (N)
$F_m(L_2)$ = Traction circle radius for the right front (N)
$F_m(L_3)$ = Traction circle radius for the left rear (N)
$F_m(L_4)$ = Traction circle radius for the right rear (N)
C_f = Front lateral force gradient (N/rad)
C_r = Rear lateral force gradient (N/rad)
C_t = Total lateral force gradient (N/rad)

However, where things get really interesting is when we look at the numbers under the hood that drives all this, and the normalised ChassisSim slip curve is shown in **table 2**.

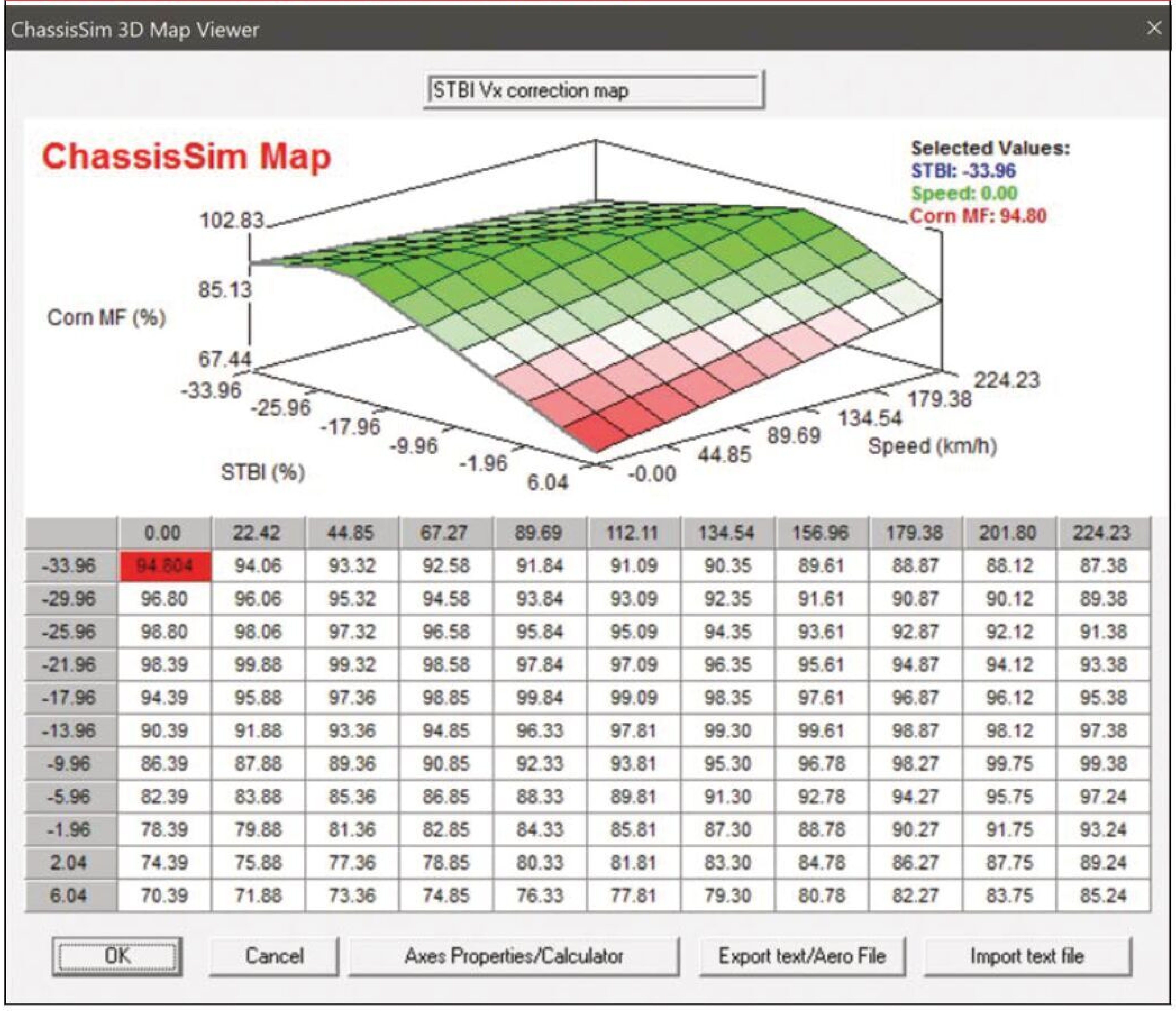
The key reason we are getting such big variations in the stability index is the gradient of the normalised slip curve. As we get closer to maximum force, you will see this is dropping off quite markedly. However, from a slip angle of four to six degrees the normalised force is only changing by 15 per cent. Given that these are the slip angles we will spend the most time in when the car is at peak *g*, cross referencing the above with **equation 1** shows why the stability index variation is so large.

Stable door

So, the key question to be asked is how do we roll this out and implement it in a lap time simulation package? **Figure 5** goes a long way to answering this.

This map multiplies the final corner speed by the look-up table. Because racecar stability is affected by aerodynamics, to get an accurate output you need to have speed as well as stability index in the picture. So, in this case ChassisSim will calculate mid-corner and turn-in speeds and will then modify these values by cross referencing the mid-corner speeds to this map.

Figure 5: Stability index corner multiplier map



	0.00	22.42	44.85	67.27	89.69	112.11	134.54	156.96	179.38	201.80	224.23
-33.96	94.804	94.06	93.32	92.58	91.84	91.09	90.35	89.61	88.87	88.12	87.38
-29.96	96.80	96.06	95.32	94.58	93.84	93.09	92.35	91.61	90.87	90.12	89.38
-25.96	98.80	98.06	97.32	96.58	95.84	95.09	94.35	93.61	92.87	92.12	91.38
-21.96	98.39	99.88	99.32	98.58	97.84	97.09	96.35	95.61	94.87	94.12	93.38
-17.96	94.39	95.88	97.36	98.85	99.84	99.09	98.35	97.61	96.87	96.12	95.38
-13.96	90.39	91.88	93.36	94.85	96.33	97.81	99.30	99.61	98.87	98.12	97.38
-9.96	86.39	87.88	89.36	90.85	92.33	93.81	95.30	96.78	98.27	99.75	99.38
-5.96	82.39	83.88	85.36	86.85	88.33	89.81	91.30	92.78	94.27	95.75	97.24
-1.96	78.39	79.88	81.36	82.85	84.33	85.81	87.30	88.78	90.27	91.75	93.24
2.04	74.39	75.88	77.36	78.85	80.33	81.81	83.30	84.78	86.27	87.75	89.24
6.04	70.39	71.88	73.36	74.85	76.33	77.81	79.30	80.78	82.27	83.75	85.24

Table 2: Plot of normalised ChassisSim slip angle derivatives

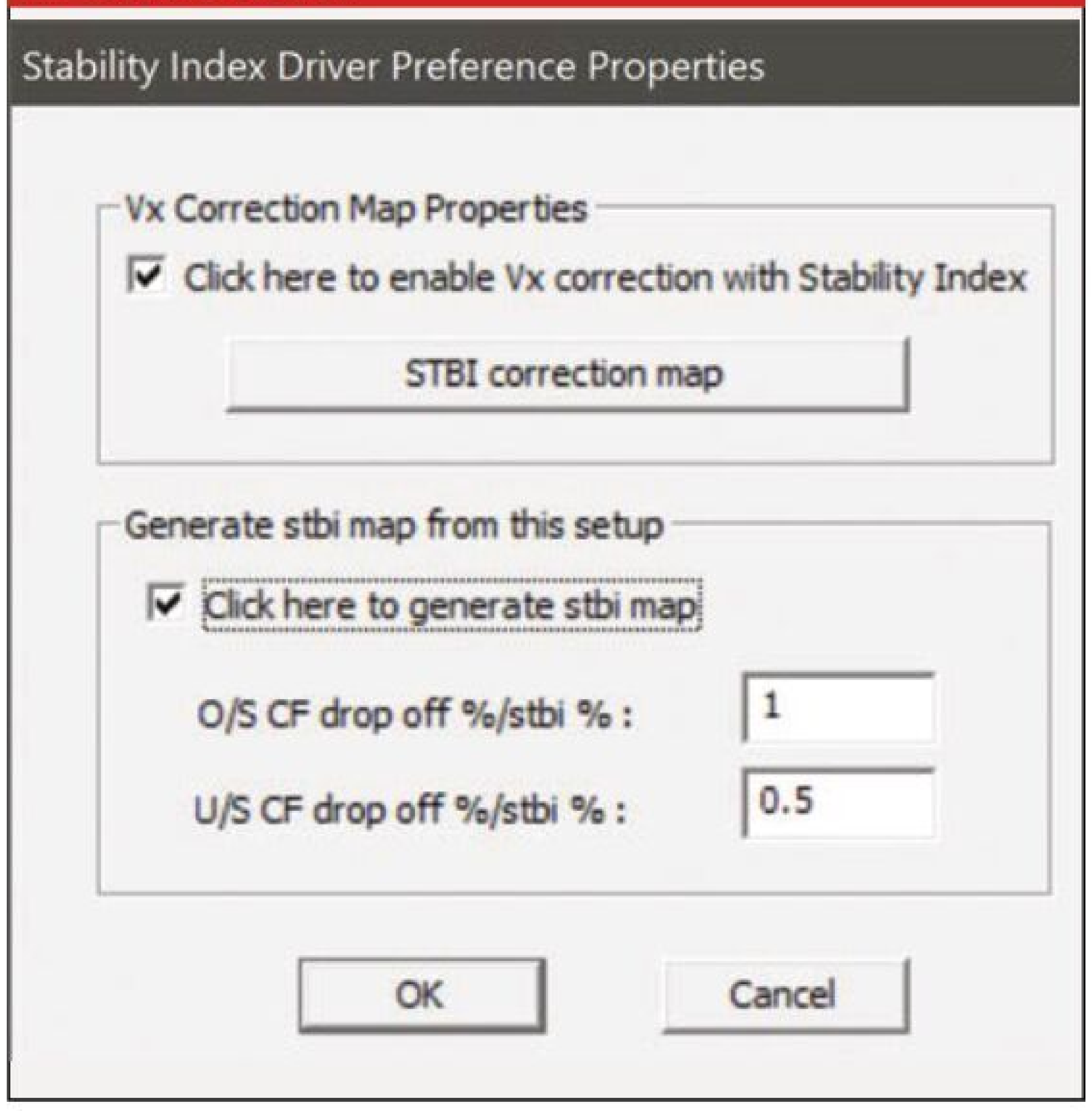
Slip angle (deg)	Slip angle (rad)	F_{NORM}	δC/dα
0	0	0	14.323
1	0.0175	0.25	13.925
2	0.0349	0.5	12.731
3	0.0524	0.69	10.742
4	0.0698	0.85	7.9567
5	0.0872	0.96	4.375
6	0.1047	1	0

The first part of this process is how to define this map. The key method is to run a simulation on a set-up that your driver is comfortable with, or rather a set-up they feel comfortable pushing the car in. This will give you the stbi *vs* speed characteristic they feel comfortable driving to. All you need to do then is to specify a map as the basis of this. This can be done manually or by using the map generator in ChassisSim, as shown in **figure 6**.

Here you simply have a slope of corner multiplication per cent *vs* stability index as a percentage. In this case the oversteer slope is one so, if the car oversteers for every stability index increase of one per cent, the corner speed will be penalised by one per cent.

In the understeer case, for every decrease of one per cent of stability index the corner speed will be penalised by 0.5 per cent. These are default numbers, but they can be

Figure 6: Stability index map generator in ChassisSim



» Because racecar stability is affected by aerodynamics, to get an accurate output you need to have speed as well as stability index in the picture

Table 3: Stability index correction results for an F3 car at Willowbank

Change	Standard	STBI correction
Baseline	61.96s	62.262s
Aero balance + 5%	61.84s	62.48s
Aero balance - 5%	62.4s	62.8s
Rear bar 600N/mm (std bar 1200N/mm)	62.265	62.58s
Rear spring 900lbf/in (std spring 800lbf/in)	62.0s	62.3s

Table 4: Stability index correction results for a V8 Supercar at Willowbank

Change	Standard	STBI correction
Baseline	69.5s	69.69s
Rear spring 70N/mm (standard 60N/mm)	69.584s	69.99s
Rear spring 50N/mm	69.464s	69.62s
Rear bar 25N/mm (standard 15N/mm)	69.564s	69.9s
Rear roll centre 300mm (standard 230mm)	69.784s	70.55s

increased or decreased depending on the skill and / or sensitivity level of the driver.

To quantify all this, we ran two tests at the Willowbank circuit in Queensland, Australia, with a live axle V8 Supercar and a twin shock F3 car. The reason Willowbank was used is that it's a notoriously bumpy circuit, so consequently it offered the perfect torture test. The F3 results are presented in **table 3**.

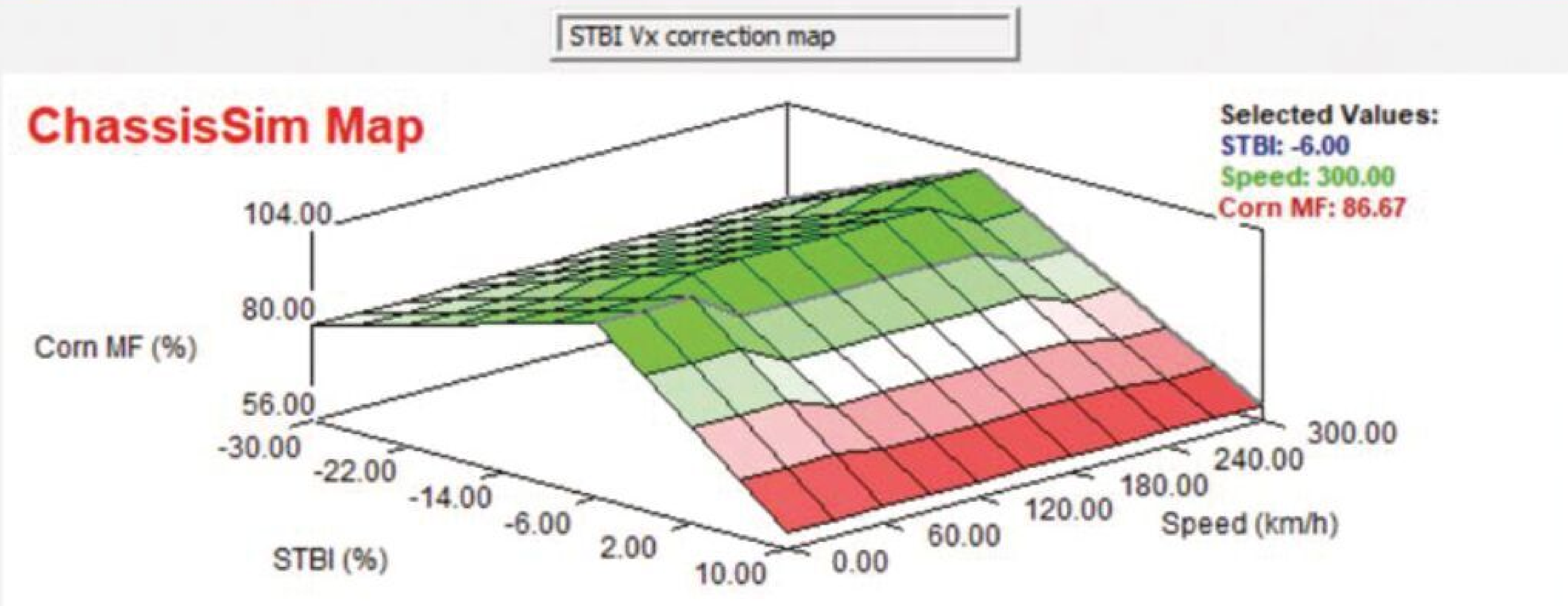
The F3 results present an interesting set of numbers. The smallest change here was the rear spring change of 900lbf/in. Since the rear bar rate is 1200N/mm, not surprisingly there aren't big changes in the base corner speed, so the effect here was minimal.

The next change was halving the rear bar rate. On standard, the delta was 0.305s, while the stability index change was 0.32s. It's starting to make its presence felt but, due to the fact the bar rates are still saturating, the tyre spring rates the effect wasn't large.

Stable manners

It's with the aero changes that things got interesting for the F3 car. When we reduced the aero balance by five per cent the delta in the standard lap time calculation was 0.44s. For the stability index calculation the delta was 0.538s, so this effect was starting to show. But things really started to happen with the forward aero balance change. The delta for the standard lap time calculation was a gain of 0.12s. The stability index calculation was a loss of 0.218s. This is where the stability index correction is making its presence felt because car stability, as opposed to corner grip, is now taking precedence in the corner speed calculation.

Figure 7: Desired racecar stability index



	0.00	30.00	60.00	90.00	120.00	150.00	180.00	210.00	240.00	270.00	300.00
-30.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
-26.00	83.33	83.33	83.33	84.00	84.00	84.00	84.00	84.00	84.00	85.00	85.00
-22.00	86.67	86.67	86.67	88.00	88.00	88.00	88.00	88.00	88.00	90.00	90.00
-18.00	90.00	90.00	90.00	92.00	92.00	92.00	92.00	92.00	92.00	95.00	95.00
-14.00	93.33	93.33	93.33	96.00	96.00	96.00	96.00	96.00	96.00	100.00	100.00
-10.00	96.67	96.67	96.67	100.00	100.00	100.00	100.00	100.00	100.00	93.33	93.33
-6.00	100.00	100.00	100.00	92.00	92.00	92.00	92.00	92.00	92.00	86.67	86.667
-2.00	90.00	90.00	90.00	84.00	84.00	84.00	84.00	84.00	84.00	80.00	80.00
2.00	80.00	80.00	80.00	76.00	76.00	76.00	76.00	76.00	76.00	73.33	73.33
6.00	70.00	70.00	70.00	68.00	68.00	68.00	68.00	68.00	68.00	66.67	66.67
10.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00

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

There is a key reason behind the lap time discrepancy between the standard and stability index correction. Given this is an F3 car, stability index will be varying with speed. Here we used only a 10 by 10 matrix and had just five corners to reference. If you increased the size of the map and you had more corners this discrepancy would be reduced.

The V8 Supercar numbers were even more enlightening, and the results are presented in **table 4**. In this case, the stability index correction now dominates the corner speed calculation. For the spring and bar changes, the standard lap time calculation was in the order of 0.1s. With the stability index calculation, it is now 0.3s. The large rear roll centre was even more pronounced with a change from 0.284s to 0.86s. Again, the differential between standard and the stability index correction comes down to a coarse correction map.

As can be seen, the stability index correction has definitely made its presence felt. In the F3 car, it prevented something that can all too often happen with lap time simulation – the more aero balance you apply, the faster you get, whereas in reality you wind up with a car that is quick but undriveable.

Meanwhile, in the V8 Supercar case, it accentuated the characteristics that were already there. This is quite significant. Where it didn't have an effect is where the chassis changes were too small to effect a change in the stability index. This does show that we aren't just making it all up, though, and that's a good thing.

The other question that needs to be addressed is whether we can define the handling we want from scratch. The answer is most definitely *yes*. All you need to do is define the map you want. A case in point is shown in **figure 7**.

As far as correction maps go, **figure 7** is as simple an example as they come. What I've done here is come up with a set-up that states that if we keep the stability index mid-corner between -6 to -14 per cent, then this will be where the maximum grip will occur. Also, this map heavily penalises any excursions from this.

Now, a key thing to take away here is that this map will vary depending on the driver. The thing that separates the Lewis Hamiltons and Max Verstappens of this world from lesser drivers is that these superstars have an innate feel for what the contact patch is doing, and can therefore tolerate stability indexes that are very close to zero.

In closing, not only is the stability index a viable way of quantifying driveability changes but, as can be seen in both the F3 and V8 Supercar examples, the stability index correction methodology produces results that actually enhance and add to the base lap time calculation. ●

Split differences

Setting up a racecar is becoming a matter of 'how fast can you afford to go?'

The development of a racecar follows the same format, regardless of application. Be it Sportscars, single seaters, off-road or oval track. In each, the task is to get the most out of the entire package, from the ground up, literally. From the track surface and its various temperature variations throughout a race, to the top of the car's wake, the target is to deliver the most efficient racecar.

That may be the ultimate goal, but reaching that point differs wildly according to budget. This really is a case of 'how fast can you afford to go?' World Championship teams have access to vast amounts of data, and huge engineering expertise in order to achieve perfection. Lower budgets, particularly in customer-focussed racing, mean less data coming from the car and more reliance on the experience of a race engineer and the development team.

While the tools are available to all teams to analyse their cars to greater detail than ever before, the regulations are often updated to try to limit the effect. The point of this is to balance performance, and not to disadvantage the lower-end teams too much compared to those who can afford it. It is also to stop teams that can afford it from going too far, and losing their programme altogether.

In the pages of this special edition we look at the technology that is increasingly available, not only to manage a team but also to monitor the opposition and maximise strategic options. The increase in the use of artificial intelligence is the next big leap in terms of preparing a car on a race weekend, allowing a computer to crunch numbers and turn out a result rather than a bank of engineers.

Until AI becomes a powerful enough tool, World Championship teams are busy finding their way around the obstacles put in their way. In Formula 1, 'virtual garages' are constructed back at base. Here, the opportunity to devour data is even greater, away from the high-pressure, intense atmosphere at the track. More engineers than ever are now working hard at the teams' bases to make their cars quicker, and to analyse the opposition and their performance.

In the days of Covid, and the resultant travel restrictions and limits on personnel able to attend races, these control centres have became more than just luxuries. Increasingly, teams are turning towards data and communications companies to deliver secure, stable data streams from the car to the pit, and from the pit to the virtual garage.

However it is not only for performance that teams use their extra help back at base. At Le Mans in 2021 Toyota found itself in a position where its two cars were about to fail due to contaminants blocking the filters within the fuel tanks' collectors, so it tasked an engineer with writing a new code to activate all four lift pumps in the tanks, a practice never before tried and tested. The computer code was sent back to base in Cologne to be debugged, and then uploaded into the two racecars, mid-race. Had the team failed in this task, it would not have achieved the one-two and ran the risk of neither car finishing the 24-hour race.

SRO/Kevin Pecks

Changing weather, particularly over a 24-hour race, makes setting the car up more challenging

Yet, these are the exceptions to the rule. For pretty much every other racing series on the planet, solid engineering practices that have been developed over decades, and learned as a craft, are just as good to make a car fast. At the Spa 24-hours one year, a Porsche driver placed with a customer team did not see the desired changes in performance using set-ups he knew would work. A new electronic measuring tool had been purchased by the team and so the engineers were sure of their numbers.

When the driver insisted they measure the car using string, it turned out the electronic system was not fit for purpose. They consequently found nearly two seconds between qualifying and the warm-up session.

Our contributor, Danny Nowlan, often writes about hand calculations, a sanity check that must *always* be applied when running or preparing a racecar. Reason being, if a number that comes from a machine looks wrong, it probably is. There is no substitute for knowing the basics.

» If a number that comes from a machine looks wrong, it probably is

The features in this edition show how complicated it is to bring a modern racecar up to the right performance level, even with experience, and even with all the technology available at your fingertips. It is often said that given the number of moving parts in a racecar, it is a miracle they start at all. However, once they do get going, it's even more of a miracle that they can perform the way they do.

Setting up and running a racecar, any racecar, is extremely challenging and there is no one solution to the problem of how to beat the opposition in any race. Each car, driver, team, circuit and race is different, which means teams are constantly chasing perfection with little chance of achieving it. And that is the joy of our sport.

Andrew Cotton