BMW RETURNS: M brand boss reveals US Sportscar plan for 2023 – p76

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Continental GT tackles Pikes Peak hillclimb

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Is it time for AI?

Can motorsport learn from financial services how to harness the power?

The upper echelons of motorsport are riddled with vast amounts of complex technology, both on and off the cars. Onboard contemporary high-end race machines, especially in the hybrid categories, you'll find an array of electronic systems. And for efficient operation, these cars rely as much on well-designed software as they do hardware.

Vehicle management typically involves using many electronic controllers interfacing with sensors and actuators all over the vehicle. In addition, they depend on highly accurate communication between various controllers using computer interrupts, timer circuits, micro controllers and more.

Years of investment in this technology has refined the interaction between different control loops, and these days engineers can drive a complex vehicle and power unit package with reasonable efficiency. But, if motorsport is the proving ground for future powertrain deployment and research and development, is it enough?

The conundrum

Currently, all motorsport categories worldwide ban the use of artificial intelligence (AI), or machine learning software that perceives its environment and takes actions that maximise the potential of its conditions. Primarily, the ban is a playing field leveller between those with the resources to explore AI's potential and those without.

Additionally, the inherent nature of AI, and its ability to modify itself during use, makes it difficult to police. There is no static code for the FIA, or any other sanctioning body, to investigate post-race compliance in many cases.

However, with the ever-increasing drive for efficiency in racecars, and manufacturers pleading for technical rules that suit research and development programmes on technology applicable to road vehicles and other forms of mobility, could motorsport become a beneficiary of AI in the future?

Should AI be used for powertrain and driveline control? It could make control loop adaptive changes to behaviour for optimum performance for a given set of conditions.

The underlying mechanisms of AI are there to analyse data, create programs for controllers and make decisions based on sensor readings and acquired data.

The challenge

The challenge related to using AI in motorsport, as elsewhere, is the volume, cost and accuracy of the data the AI system must analyse before making its decisions. The more parameters an AI system has inputs for – in a modern racecar, there are already hundreds of channels supplying information – the harder it is to accept and process the data.

The accuracy of this data is absolutely critical. As per a human analyst, an AI system decides based on its evidence, and 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 in other industries, making it more suitable now than in the past. This type of computing access is becoming widespread throughout the Formula 1 paddock, so it isn't too far fetched.

Graphcore

Illustration of a deep neural AI network architecture called ResNet. The visible clustering is a result of the communication between processors in each layer of the network

With the constant drive for more sustainable motorsport programmes and race series, running the powertrain in operating conditions that could further improve efficiency and prevent failure is an application where the sport as a whole would benefit directly.

Typically, where an engineer would analyse data from a powertrain failure to identify the instantaneous moment of failure, an AI system could analyse *all* the parameters around when it failed and potentially identify the cause.

It's not simple, as each operating parameter of the powertrain, their operating window, the factors that influence them and the influence any one parameter has on another must all be understood. This would have to be 'taught' to an AI system for it to work effectively.

The ability to prioritise each operating parameter during the analysis is vital to the system's success. For example, if it's configured too acutely – known as overfitting – AI could identify a situation where a *previous* engine failure occurred at a certain rpm and then only look at that particular rpm as the cause for any further failure. Of course, that may or may not be the only point at which the powertrain fails.

If the programmers over-extend rpm scope on either side of the exact rpm at which a failure occurred, then suddenly the system has a bigger window to interpret, reducing the accuracy of the program. Also, most rpm will not fail the engine, so the system should categorically avoid no rpm (within the given operating range). The analogue concept of 'too much rpm', rather than a specific numeric rpm limit, must be 'taught' to the digital computer system.

There are ways to make this happen, as proven in the AI networks that operate in the world's most advanced financial systems to great success, with many takeaways that help companies in various sectors work financially efficiently.

Despite the motorsport-specific challenges, AI could provide vital input into sustainability, and help pave a more direct way to the carbon neutrality the industry must achieve in order to remain relevant.

Let us not forsake the technological advances already made in motorsport that could re-shape the future of energy storage and deployment, and use the tools at our disposal to investigate new strategies for the future.

Let us not forsake the technological advances already made in motorsport that could re-shape the future of energy storage and deployment

Chicanery

One series needs to introduce one, another needs to stop it

This year's 105th Indy 500 ran true to fascinating form. After first-lap jockeying for position, and the sponsor-pleasing buzz of leading 'the world's most famous race', it soon settled into a fuel-saving, drafting snake of cars leading up to the first fuel stops, from which most team strategies would then evolve.

Yellow caution periods, pit fumbles and closures and fuel consumption differences then jumbled up the order and the strategies from there on in. The final few laps culminated in an edge-of-the seat finish, just half a second separating winner and runner-up after 500 miles and over 2½ hours of high speed racing. Exactly what brings the fans flooding back, in person and on TV, year after year.

Nervous brake down

Not so usual this time was the number of pit-lane spins and speed limit violations caused by cars entering far too fast, drivers seemingly unable to slow their machines down enough. This is not uncommon at Indy, but not to the degree experienced this year with at least five incidents, including one significant crash.

The cause of these heart-in-the-mouth dramas appears to be due to some teams overdoing the use of brake caliper pad retraction systems. These are designed to ensure there is zero contact between pads and brake discs, ensuring no fractional mechanical drag penalty, and are used only on superspeedways where braking doesn't normally occur on track. They are the opposite of the very soft springs sometimes employed on road circuits to overcome the 'knock-off' of the caliper pistons that can occur at the end of long straights, or after a pit stop.

The effect of the pull-back set up can be to create a 'long' brake pedal, which needs pumping by the driver before full deceleration can be achieved. Entering the pit lane at 200mph+ to slow down to 60mph, any delay in retardation can be disastrous. One might imagine drivers would indulge in some judicious left-foot braking toward the end of the pit-in lap to get the pedal nice and firm but, for whatever reason, this didn't always seem to happen, albeit a shared responsibility between driver and race engineer.

This practice is highly dangerous and should surely be banned forthwith. Apart from the pit lane hazard it clearly presents, if a car spins or crashes in front of another on track, there is no time for the following driver to pump the brakes to reduce impact. Instant reaction is essential.

The pit entry at the Brickyard must be one of the most dangerous there is. I recall watching from the pits when someone lost it out of turn four and smacked into the wall, sending the complete engine / transmission package whistling down the pit lane just a few yards from me – mercifully without killing anybody. The protection here has been markedly improved since then, but the fundamental issue of preventing such a possibility still exists, including the brake hazard mentioned.

Matt Fraver/IMS Photo

This year's Indy 500 was marred by a number of drivers spinning in the pit lane, including Stefan Wilson. That there was just one serious crash as a result was luck

Strong emotion

Tradition is a strong emotion in the USA, and any changes to the format and history of the 500 are likely to be resisted, but I see no reason why a chicane cannot be established to slow the cars pre-pit entry. This would involve the entry commencing before, rather than after, turn four, linking up with turn three of the road circuit prior to actual pit lane entry. It might take a bit of the drama out of the fuel and tyre stops, but with wheel guns flying, the occasional fuel fire (despite water being squirted on the fuel buckeyes), tyre smoking releases etc. there is plenty left.

IndyCar has a great record of improving safety, hideous though the cockpit screens may be, and it is still amazing how drivers, thankfully, so often walk away virtually unscathed from high-impact crashes. Pit entry at Indianapolis should not be an outlier to this continual progression, this time with refuellers and tyre engineers at risk.

Missing nuts

Elsewhere, chicanery is no more evident than in NASCAR, where recently suspensions and fines up to $10,000 were issued to crew chiefs for securing only four of five lugnuts during wheel changes, in order to save time with NASCAR's archaic wheel fixings. It may be that the cars were safe missing one lugnut, but it is clearly not for the crew chiefs to decide. Such cheating has been going on for a very long time, but penalties don't seem to have deterred these chancers. Some no doubt get away without being caught, mid-race anyway, but I'm glad that good ol' boys have accepted reality and the single wheel fixing for 2022 will be implemented.

F1 is more closely monitored, but some criticisms have been aired regarding the actions of race director, Michael Masi. It has to be said that since taking over from the late Charlie Whiting, he appears to have successfully carried out a very demanding role. However, a tendency to make up, or alter some regulations 'on the hoof' has crept in, notably the application of track limits and, at the end of the Baku GP, deciding to not penalise drivers who failed to properly respond to double waved yellow flags following Verstappen's crash.

Saying all drivers had been speeding and therefore, if one was to be penalised, they all should be, is precisely the point. Yes, they *should* be, whether the correct penalty is a fine or three places back on the grid at the next race. Given that some might have not committed any wrong – certainly those already out of the race – the latter punishment could have made the grid for the French GP two weeks later quite interesting.

This no action does go beyond the remit of race director as it ignores an important safety regulation – McLaren's Andreas Seidl is right to complain, even if his reference to Lando Norris' qualifying penalty is not entirely relevant.

The final few laps culminated in an edge-of-the-seat finish… Exactly what brings the fans flooding back, in person and on TV, year after year

Standing on the threshold

Forget emotion, science and academia can provide the answer

In the Bump stop column in the last edition of *Racecar Engineering*, our esteemed editor quoted from a conversation with GT supremo, Stéphane Ratel. Stéphane probably understands the meaning of the word 'sport', as in motorsport, better than just about anyone else, having built up the GT3 series around the world, catering for owners and drivers who participate in motorsport for the sheer pleasure and sport of it. His two comments: 'Electric is about mobility, not about sport', and 'Every category that relies on direct manufacturer involvement is doomed' bring into focus the key questions facing international motorsport in the next decade:

1. What is promotionally important to the automobile manufacturers?
2. Can motorsport provide this promotion?
3. How does the sport function without them?

The auto industry exists to provide mobility on the road for people and goods. A big part of the oil industry's business and profitability is to provide the energy to fuel this mobility. But things are changing. For the last century, since kicking horses off the road, the automobile industry has invested widely in massive factories for making piston engines, and all that goes with them.

Significantly, the one country that has not arrived at this level of industrialisation, until recently, is China. In the same way that India and Africa are not encumbered with landline telephone systems, China does not have large, potentially-stranded, ICE manufacturing assets.

Transition period

The industry is in transition as it transforms away from fossil fuel-based mobility to renewable electrical energy. There remains the debate on how that electric energy is stored and converted into useful work to propel cars, trucks, buses, vans etc. The current candidates are:

- Direct electrification: renewable electricity – batteries – EVs.
- Hydrogen: renewable electricity – hydrogen – high-pressure tank – ICE, or fuel cell EVs.
- e-Fuels: renewable electricity – CO_2 capture – e-fuel – liquid-fuel tank – ICE.

Industry debate about which approach is the right one has raged for some time now, each side according to its vested interests.

Formula 1 had bio race fuel as long ago as 2009 and is set to go big on the technology in the near future, but what does that have to do with regular production cars?

More recently, academia has examined the key issues: overall efficiency; infrastructure requirements; CO_2 mitigation, and the resulting costs. The conclusions have very recently come together in, among other publications, a report by the Potsdam Institute for Climate Impact Research, published in *Nature Climate Change*:

> *Potential and risks of hydrogen-based e-fuels in climate change mitigation*, Ueckerdt, Bauer, Dirnaichner, Erverall, Sacchi, and Luderer; 6 May 2021. (www.nature.com/articles/s41558-021-01032-7)

What academia does is to look at the science that determines the fundamental principles behind each approach. In the end, automobile consumers will decide, and the criteria they will apply are: cost; pleasure of ownership; pleasure of driving (or of being driven by a slice of silicon).

Direct electrification

Direct electrification of vehicles is around 77 per cent efficient, from renewable source to the wheels. The technology is now pretty mature, and is getting cheaper all the time. Transmission and distribution are well developed in the western world, and the scope for local generation and storage is being intensely developed. The energy available greatly exceeds the world's needs.

Storage in the vehicle, however, is both heavy and expensive, but those parameters are on steep reduction curves. Conversion to useful work is both low cost and very efficient.

Hydrogen

With VW, Mercedes and Scania having recently rejected hydrogen as an energy storage system for road vehicles, all having explored the potential technologies over a number of years, I am reminded of a Lotus Engineering fuel engineer's remark: 'When hydrogen's properties change, give me a call.'

Conversion efficiency from renewable electricity via electrolysis, distribution, storage, conversion by fuel cell, batteries and a motor is around one third that of direct electrification. This, plus the cost of building a hydrogen vehicle, is what has led to its abandonment. Herbert Deiss, VW's chief executive, referred to the Potsdam Institute report in his anouncement.

Toyota recently ran a hydrogen-fuelled ICE car in a 24-hour race in Japan. It completed the race, but spent four of the 24 hours being refuelled.

e-Fuels

That same Lotus engineer also remarked, 'The best thing you can do with hydrogen is attach carbon atoms to it.' This is what the emerging e-fuel industry is doing.

What academia does is to look at the science that determines the fundamental principles behind each approach

It takes the products of hydrocarbon combustion – water and CO_2 – splits them and stitches the hydrogen and carbon atoms back together to form a hydrocarbon fuel, restoring the energy emitted by combustion with electricity and / or heat.

These processes, electrolysis, CO_2 capture and hydrocarbon synthesis require significant renewable energy in the form of either renewable electricity, solar-powered biochemistry or renewable heat. Results in a source-to-wheels efficiency is around one fifth that for direct electrification.

When you follow the science, direct electrification is the only technology that makes long-term sense for road transport

Yes, the process recycles CO_2, but not at 100 per cent, and compares poorly to the previous two technologies, which do not emit any CO_2. It is also the only one of the three that emits local pollutants, such as particulates and NO_X, continuing to affect air quality in cities.

Andrew Ferraro

Electric sport is raising the profile of EVs, but manufacturers are turning away from Formula E and Electric GT

The advantages of e-fuels to the automotive and oil industries are obvious. Any fuel, provided it is a drop-in fuel, already has a distribution system, and the energy density beats batteries and high-pressure storage tanks. Their conversion to useful work is via a 25-30 per cent efficient ICE, which the automobile industry makes in large quantities using established assets. There is little demand-side investment needed.

Ups and downs

Back in 2012, when Audi invested in Joule Unlimited to develop synthetic fuels from sunlight, water and CO_2 using a cyanobacteria, I wrote enthusiastically in *Racecar Engineering* about their potential. However, investment in the project, which had grown to a fully functioning demonstration facility in New Mexico, dried up in 2017 as oil prices plummetted to under $50 per barrel, and investors began to see the potential of what Tesla was doing, and its shares doubled for the first time.

The Potsdam Institute predicts e-fuels will not be ready by 2030, and certainly not economically. If the automobile industry prolongs the commitment of road transport to the ICE, and e-fuels cannot be delivered, the oil industry believes we will simply have to revert to cheap oil, prolonging their profitability and the problems society has today.

The ICE and fossil fuel proponents who fight back against EVs by claiming that there will not be enough renewable electricity to support the transition by 2030 seem to ignore the fact that hydrogen will need three times the generating assets, and e-fuels five times, to provide the same amount of useful work to propel vehicles.

When you follow the science, direct electrification is the only technology that makes long-term sense for road transport, with hydrogen and e-fuels having roles in other forms of transport eg ships and aeroplanes, where storage capacity and energy density are critical.

How quickly this is achieved depends on the automobile and oil industries' efforts to slow it down, and governments' responses to their lobbying in the form of subsidies and a tax structure to replace fuel taxes.

China, without the ICE and insufficient oil assets, has committed to EVs and batteries. The country's industries are being centrally encouraged to build an automobile industry based on them. They are poised to go out into the west to sell their products in competition with an unprepared western automobile industry, which is only just waking up to the threat.

China's indigenous EVs are cheap and cheerful (okay, so they may be mauve or pink inside and out, which is a bit weird, but…) and ideally suited to inner city and suburban mobility needs. Many are priced in China at under $6,000. Cities in China already support fleets of e-buses and e-taxis, tens of thousands strong and growing.

Pleasure seekers

So, what will the automobile and energy industries look like in five and 10 years' time? What areas of motorsport will be suitable to promote their products and technologies? Stéphane put his finger on the answer: motorsport is about sports, not mobility. While there are people who enjoy, and can afford, the pleasure of driving, in the future they will want light, powerful, noisy, ego-boosting cars. While goverments allow, manufacturers will make and sell these products, as they have already made the investment and are profitable.

As Porsche has realised, teaming up with Siemens Energy, among other partners, to develop e-fuels in Chile, they will need them to be permitted on the road and track.

Manufacturers will also need motorsport to promote these products and establish their sporting credentials. These cars are the GT and Sportscars.

Maybe the German automobile industry – here that's referring to Audi, BMW and maybe Mercedes – are pulling back from Formula E because they understand this. They now have DTM and GT3 to promote their GT cars, and can see that few private car customers are really interested in battery and electric-powertrain technology, any more than they are about the same type of powertrain in their robot mowers and vacuum cleaners.

Road tests of EVs talk of nothing but style, space and inevitably range (which is not just battery capacity, but also charging rate and availability – Tesla's great trump card), along with telematics. No EV has yet appeared with a 'Li-ion' or 'Br-Per-Mag-Sync' logo on the back.

We are heading towards a mobility future where customers, led by the young, do not necessarily *want* to have to drive a car, nor own an expensive asset that sits outside depreciating for 95 per cent of the time.

As Stéphane points out, the motorsport industry needs to figure out, quickly, how to operate and survive by concentrating on sport, not mobility. Manufacturers are going to be almost 100 per cent focussed on electric mobility, and so unlikely to significantly support motorsport in the future.

The motorsport industry needs to figure out, quickly, how to operate and survive by concentrating on sport, not mobility

Max attack

Bentley has taken its Continental GT and turned it into an eco-friendly monster for the Pikes Peak hillclimb. **Racecar Engineering** ***investigates***

By ANDREW COTTON

Bentley may have cancelled its factory GT3 programme, but the Continental continues to race in private hands and is still available for sale. However, the factory turned its attention to an entirely new challenge for its latest version, a Time Attack on the Pikes Peak hillclimb using a fuel that produces up to 85 per cent less greenhouse gas than regular fuel.

The base car is run by Luke Clayton, a long-time Bentley customer, but the factory used his hillclimb experience, and car, to create its GT3 Pikes Peak. Using experienced team, Roger Clarke, and engine partner M Sport, Bentley pulled together some incredible expertise in order to make the attempt a reality. They needed it. With just 16 weeks from greenlight from the board to the event, time was in short supply.

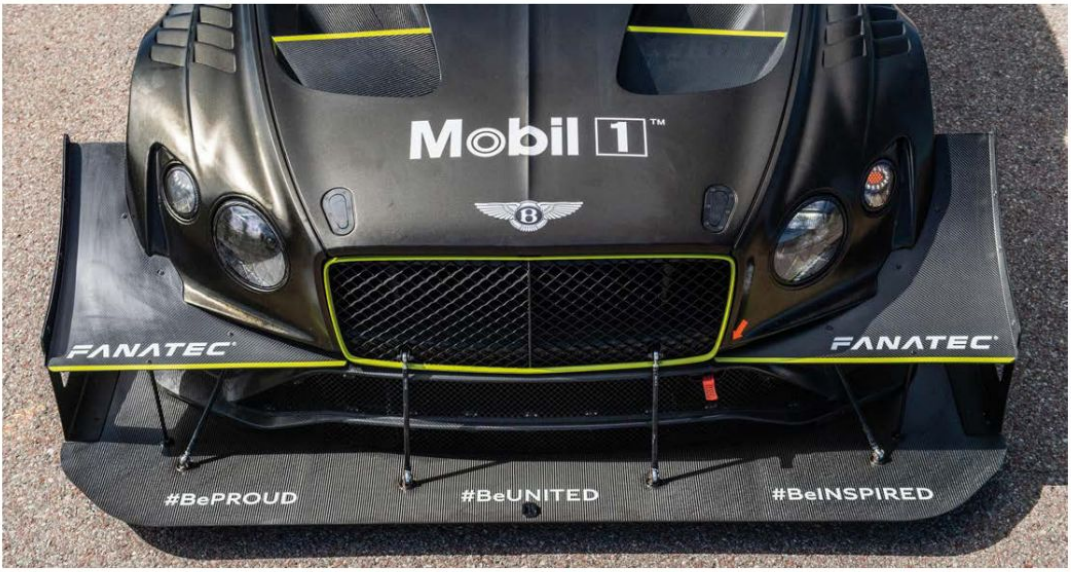
The basic car is pretty much unchanged from the GT3 car that has won internationally, not least the Bathurst 12 hours in 2020. The chassis remains the same, as does the suspension, although settings have changed dramatically for the totally different demands of the Pikes Peak track. Far from the smooth asphalt that adorns most permanent circuits, with a combination of fast flowing corners and long straights, Pikes Peak has more first gear corners, and the average speed needed for Bentley to claim the Time Attack 1 record was just over 78mph.

Camber compensator

'It's the same chassis in terms of bodywork as the GT3 car, we just changed our approach in terms of set-up,' says David Argent, technical manager motorsport for Bentley Motors.

'For a traditional track car, we would run through a higher camber set-up on stiffer springs, but you have to revise your thinking when you are doing something like a hillclimb event, where you are on a public road with a lot of bumps in it, kerbs and drain holes.

A big design criterion was we really didn't want any turbo lag on this thing because there are so many first gear hairpin exits



Car's startling aero kit, with giant dive planes and even more dramatic rear wing, was designed in CFD and validated on track in the UK. Downforce is up by 30 per cent over its circuit racing spec

'We have taken a lot of camber out, from around five degrees to two and a half on the front and from three and a half to one and a half on the rear, so we have really stood those tyres up and optimised the rear contact patch.'

That has meant the team playing with the pressures to ensure minimum drag, and choosing Pirelli's hillclimb tyre for grip. They didn't have the development programme to be able to start playing with profiles or compounds, but went to the event happy with the basic tyre.

'The camber is more focussed towards giving us that low-speed traction advantage out of the hairpins and in low-speed corners. It's a similar thing with the [anti-]roll bars. We have gone soft on this just to optimise weight distribution and optimise grip,' says Argent.

There were a few performance parameters that were also left untouched due to a shortage of time, including playing with the gear ratios for the lower top speeds anticipated. The car therefore runs with the standard ratios in its Ricardo gearbox, although partner, Mobil, produced a specially formulated lubricant for the car, while the rear driveshafts have been increased in diameter to cope with the extra power.

Traction control

Traction control settings were also developed, but not outside what is available to the GT3 customer teams.

'Because we did a good job on the GT3 car, the algorithm that the car uses for traction control still applies,' says Argent. 'It's a percentage slip over time, and how hard it cuts, that logic was carried across and nothing needed to be changed. All we did are the mechanical changes to stand the wheels up and gain traction from that.'

Fuel cuts are an obvious way to limit power under lower traction conditions, and again Bentley's base car provided all the hillclimb team needed.

'We have not tested it in isolation, but it has been something we kept an eye on during running,' says Argent. 'In first gear we just pull a little boost because otherwise the wheels would just spin up, and that's the slowest way to pull away from a corner. We get to the point between just getting a bit of TC intrusion, but where you are able to control the car and still be quick.'

Aerodynamics

The nature of the course dictates the cars need some extreme engineering solutions. Altitude is the most obvious one. With the course starting at just over 9000ft above sea level, rising to more than 14,000ft, the air is much thinner towards the top. That affects aerodynamics – hence the wings, cooling and the extraordinary ducts in the rear windows and boot lid – and power, with far less air getting into the engine than normal. Again, the Bentley development team had to find solutions for each of these issues in a hurry.

Aero is clearly the most striking point of the car, with giant dive planes at the front and a rear wing up on stilts at the back. The kit was designed in CFD and validated at Anglesey circuit by Bentley's factory GT3 drivers, but the team claims, despite the looks, and the fact it helps to produce 30 per cent more downforce at sea level, it is not that extreme.

> **The camber is more focused towards giving us that low-speed traction advantage out of the hairpins and in low-speed corners**

'The target here was to keep the aerodynamics we have on the base car now, but get an increase of around 30 per cent to cope with the air density reduction through altitude,' explains Argent. 'We have restrictions through the regulations. We are only allowed to increase it by 30 square inches, which is about 10 pieces of A4 paper. We had to strike the balance between that and keeping the same area of balance, so that at the very upper limit at high speed its tendency is to go to understeer, not snap oversteer, because that's obviously safer for a driver. The last thing that you want going up the mountain is snap oversteer at high speed.'

The team also beefed up the cooling with a second system at the back of the car, fed by the scoop on the boot lid. This contributed to the weight increase of just under 100kg, compared to the GT3.

With the reduced air density and lower top speed anticipated by the team, airflow cooling is much reduced, so the team has turned to water-cooled brakes and gearbox. Previously, the team competed at the event with production cars, and saw high water

The target here was to keep the aerodynamics we have on the base car now, but get an increase of around 30 per cent to cope with the air density reduction through altitude

temperatures, up to 138degC at the top of the hill, so have had to try to mitigate that.

However, the biggest challenge for the team was running on Esso's 98RON blended fuel that, it is claimed in Bentley's press release, will reduce greenhouse gas emissions by up to 85 per cent. In order to do that, while running at extreme altitudes and in temperatures that can range from more than 25degC to cold enough to snow at the top of the run, the development team at Crewe and M Sport in Cumbria have worked hard to adapt the engine accordingly. Target power was north of 800bhp at sea level, with 1000Nm of torque from the 4.0-litre V8 engine.

Delivering that power at sea level was, however, not the point of the exercise.

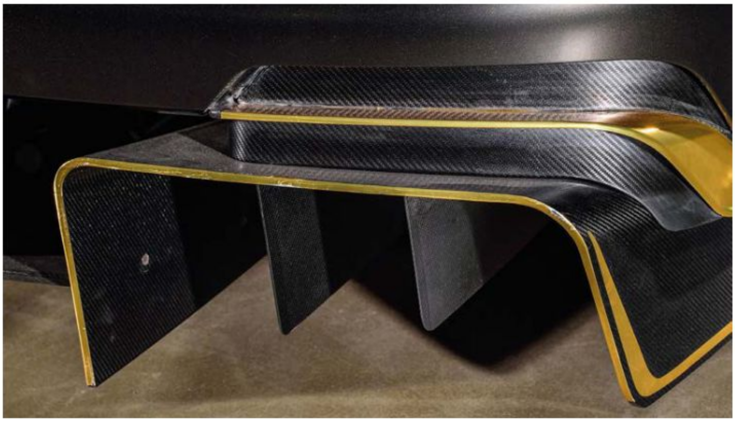
Power at altitude

'We wanted to target around 800-850bhp at altitude, so you can use some extrapolation to work out what that means at sea level,' says Argent. 'The intention was never to have a car that functions particularly well at sea level because we were targeting the turbo housings and turbo sizing to work at altitude.

'At a certain point you will get traction limited because you can't just stick 1000bhp and 1400Nm of torque through a rear-wheel drive, you just won't be able to use it.'

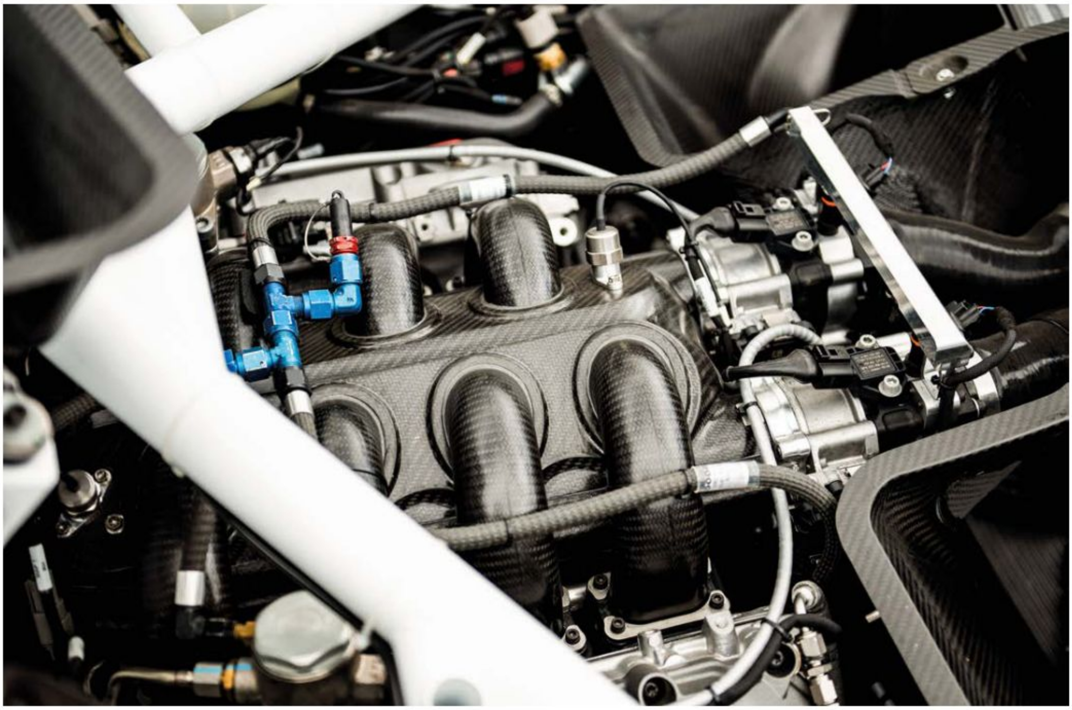
The engine runs in GT3 racing with restrictions placed on it by the Balance of Performance, so just removing these went some way to increasing the power before any other work needed to be done.

'Traditionally, we're restricted by BoP in GT3, and you can be running anywhere from 525-550bhp up to 600,' explains Argent. 'So, you're talking a 300bhp delta to this engine. Obviously, that's not comparing apples with apples, though, because we're comparing an altitude engine to a sea level engine. So, it was a bigger task than the numbers describe.



Much of the aero increase was necessary due to the reduction in air density as the track winds uphill to an altitude of over 14,000ft

Camber was a major focus in the suspension tuning, reducing it both front and rear to enlarge the contact patch for the wildly different surface and cornering requirements of Pikes Peak



The base 4.0-litre V8 engine runs on Esso 98RON blended fuel for reduced emissions, but it needed bigger turbos and additional port injection to produce the extra 250bhp required at altitude

'The main area we were focusing on in development was making sure we get enough fuel into the engine to be able to produce the additional power we require.'

Lag reduction

'We looked at injector sizing, fuel rails and, to complement that, we needed to get more air in, so we went for bigger turbos on the engine – ones that were sized appropriately. We have a large compressor intake with a surprisingly small turbine housing to be able to compress that less dense air and get the least turbo lag out of the car.

'A big design criterion was we really didn't want any turbo lag on this thing because there are so many first gear hairpin exits. You'll just drop seconds every single one if you have lag.'

In order to get the fuel into the chamber, the team added port injection to the engine to augment the direct injection the car runs in GT3 spec.

'We were quite fortunate we understood the airflow through the intake,' says Argent. 'We've got a common intake manifold on the engine, and it was already well understood, the flow path through there was designed for racing using CFD.'

Compensating for the reduced air density, the team mapped the engine to run to a boost target figure controlled by the turbo wastegates to drive as much air as possible into the chamber for as much of the climb as possible. This was one of the first things that had to be redesigned at the start of the development process as the base map the team was using at sea level couldn't produce the desired boost targets at Pikes Peak altitude, even with the wastegates fully closed.

'We have done some optimisation since we have been testing to get the right size turbo housing to allow us to have the desired response and meet our boost targets,' says Argent. 'We had to go to an external wastegate as well because the in-turbo wastegate found on the turbocharger units on the GT3 car weren't big enough for what we needed to control the boost.'

Boost pressure is high, at 2.2bar, and that had a further knock-on for the engine design. Higher boost pressures mean increased in-cylinder pressures, and consequently the team had to change the pistons and con rods to cope with the increased loads.

Fuelling the issue

The fuel itself was critical to the power output, and here Bentley has been working using Esso's standard fuel.

'There are no additives that we have added to it for our application and, in terms of knock resistance, it has been very stable

We have treated it as a more traditional, stable fuel and have been reliant on the turbo change itself to bring the oxygenation element to the combustion chamber

for us,' says Argent. 'We have had to do surprisingly little with the fuel system. We have treated it as a more traditional, stable fuel and have been reliant on the turbo change itself to bring the oxygenation element to the combustion chamber, rather than using fuel additives to compensate.'

The team has used pre-intercooler water injection to drop the temperature of the air entering the combustion chamber as a further knock control parameter. They did try post-intercooler water injection as well to help bring temperatures down further still, but found that saturated the mixture and started to lose performance.

In terms of the exhaust, partner Akroprovic provided the necessary expertise to be able to deliver the appropriately tuned product for the application.

'We provided them with all the data from what we were expecting to produce in terms of flow and the turbo sizes we were going to use and they made recommendations from their side on what sizing we should go to. That's how we ended up with our manifold and exhaust designs,' confirms Argent.

The real challenge

Temperature control is one of the key unknowns in the design of the car, since the hillclimb running order can be unpredictable. The cars can set off early in the morning with low ambient temperatures at the lower levels and remain more consistent as they run to the top of the hill. On the other hand, a crash on the mountain can delay matters, so cars may then compete in higher temperatures, and they don't get the chance pre-race day to practice the entire hill.

Preparation for the competition only allows runs on one of three sections of the hill, and combining the three in one go needs some calculation and extrapolation.

'That is the real engineering challenge,' admits Argent. 'You have got all these little sections that you have to piece together from your testing and make the best experienced judgement on race day about how to run. From the runs we did with the Continental GT road cars, our water coolant temperatures were fine, and there is never a concern.

'But on race day, when you add the three sections together, and you get thermal load through the 'Ws' section of the course – which is the worst area because it is very aggressive on the gearshift but at very low speed, so you have no air passing over the radiators and you are hammering the engine – then you can run into trouble. We reached 130degC water temperature in the road car, so it's these areas the racecar cooling compensates for.'

The team uses Mobil 0W-30 polysynthetic oil in the car in order to try to reduce the heat from the engine, but it is no different to that used in the GT3 competition car.

'It is proven for these engines,' says Argent. 'We have oil-to-water heat exchangers, and the focus is on keeping water temperatures low. Hence, we went for the second radiator as that keeps everything else a lot cooler.'

There was no need to experiment with materials in the engine, having already run at the high ambient heat of Bathurst, where the car performed within parameters. However, the team uses some 3D printed parts extensively in the Pikes Peak challenger for optimisation as the rules don't restrict its use.

We also have 3D printing on a lot of the aerodynamic features, purely so we can change them around and play with the different forms of it

'We use 3D printing for things like the exhaust collector, which is an inconel system,' confirms Argent. 'We also have 3D printing on a lot of the aerodynamic features on the car, purely so we can change them around and play with the different forms of it. And the intake system at the back end for the new radiator is all 3D printed as well.'

With the 'works' GT3 programme completed, and with Bentley now holding records at Pikes Peak, there seems to be very little more the company can do in terms of racing exposure with its current range of products. This could very well be the last of the Continental GT programmes run by the factory, but what a dramatic programme it has turned out to be.

Pikes Peak regulations are very different to GT3, so the team took full advantage of them, 3D printing items such as the rear air intakes for the second radiator, deemed necessary to keep temperatures stable in the low-speed, high-stress, 'Ws' section of the course

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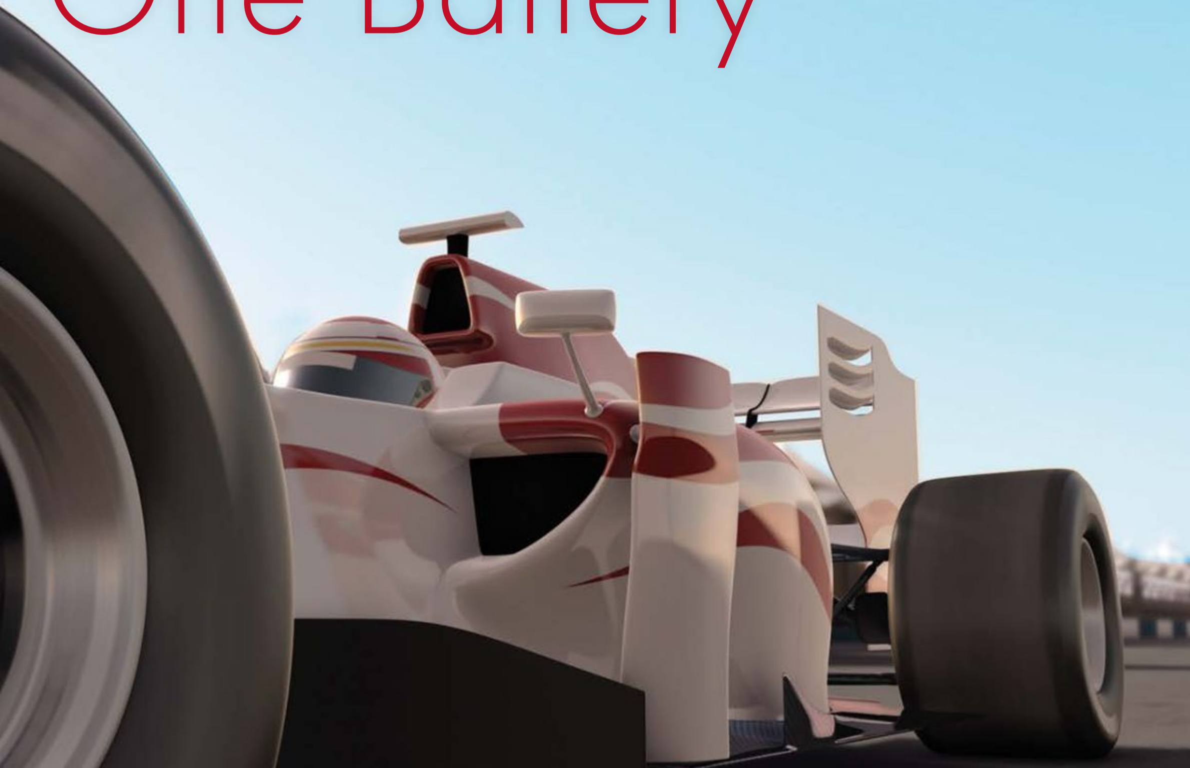

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Target practice

In the first of two articles, Racecar *analyses the new LMH class regulations, focusing on performance-critical areas*

By ANDREA QUINTARELLI

Photos: XPB

The Hypercar field for 2021 comprises a grandfathered ORECA chassis run by the Signature Alpine team, two Toyota GR010s and the Glickenhaus 007C, all performance balanced in the FIA World Endurance Championship

Le Mans Hypercar (LMH) class is here, after a long and complicated gestation that saw the rules change several times before settling on a plan manufacturers could use to construct their cars. *Racecar Engineering* understands there could still be changes in some areas, as uncertainty, mainly related to new car performance, such as that of the Glickenhaus 007C, remains.

One of the consequences of the performance targets set for this new class is that the performance of the LMP2 cars had to be aggressively reduced in order to achieve the necessary differentiation between itself and the LMH class. That has proven chaotic, and has seen LMP2 holding different technical rules in every championship in which it competes worldwide.

The ACO gave the LMH class a target race pace in Le Mans of about 3m30s, about 10 seconds slower than previous generation LMP1 cars, and very similar to how the LMP2 class performed until 2020.

From the beginning, the primary driver of LMH rules was to have a top-tier class where manufacturers could compete, while deploying much lower budgets than LMP1. The ACO achieved that goal by setting very strict performance boundaries on critical areas of the car, including powertrain and aerodynamics, along with relatively easy-to-achieve targets, making extreme development efforts redundant.

The rules also allow for incorporating some road car styling cues into the LMH racecars without grappling against the aerodynamic performance target.

Despite the complicated process of bringing it all to fruition, there are many reasons to be happy about the LMH rule set.

Open door policy

Primarily, the ACO and IMSA agreed to have the Le Mans Hypercar and the new-to-come LMDh cars (LMDh is the new, top Prototype class in IMSA, starting from 2023) racing together in the 24 Hours of Le Mans. Additionally, this should open the door for other iconic races to combine the two top classes in the respective series, like the 24 Hours of Daytona or the 12 Hours of Sebring.

The phrase of the day is Balance of Performance (BoP), as the two classes' regulations and philosophies will have some common points, as well as some significant differences. This could cause headaches to the technical groups responsible for making racing between LMH and LMDh cars fair and appealing.

Rule set main points

A large part of the LMH class technical rule book is publicly available. Interestingly, though, some critical appendices, including the one about aerodynamics, can only be accessed by the manufacturers.

Without going into exact details, some areas are fascinating with regards to performance. First of all, LMH cars are bigger and heavier than previous LMP1 vehicles. The minimum weight is set at 1030kg for the car without driver and fuel (some 150kg more than LMP1, depending on the car's architecture), with the maximum width and length now 2m and 5m respectively (LMP1 was 1.9m and 4.65m). The wheelbase must be less than 3.15m.

With weight being an essential part of the BoP process, Toyota was given a weight 'penalty' of 10kg before the season even started, to compensate for the performance advantage provided by its front axle-mounted e-drive system.

LMH cars are powered by an internal combustion engine only, or by a hybrid powertrain. In the latter, the traditional engine works with an electric motor that drives the front wheels, very similar to LMP1 cars.

Figure 1: LMH power curve provided by the rule book (sum of power measured at each driveshaft)

Engine speed (N/Nmax)	POWER (kW)	ADJUSTMENT (kW)	
	500	LOW	HIGH
0.550	246	236	256
0.575	269	258	279
0.600	289	277	300
0.625	309	297	322
0.650	330	317	343
0.675	351	337	365
0.700	372	358	387
0.725	393	378	409
0.750	413	397	430
0.775	432	415	449
0.800	449	431	467
0.825	464	445	482
0.850	475	456	494
0.875	485	466	505
0.900	492	472	512
0.925	497	477	517
0.950	500	480	520
0.975	498	478	518
1.000	495	475	514
1.025	427	410	444

The gearbox can have a maximum of seven forward gears. Teams may only homologate two sets of gear ratios, one presumably tuned to fit the very high speeds of Le Mans, leaving the second set for all other tracks of the season.

Consequently, the overall approach to energy management is very different compared to LMP1. In the last few years, fans have become used to teams managing the energy available for combustion and electric engines during a lap, or a stint, with engineers developing complex strategies for power deployment during acceleration phases, where it pays the most in terms of lap times, and coasting (slowing down by lifting off the throttle) before braking points. This has allowed teams to save fuel to remain within the given energy boundaries but still maximise performance.

Coasting should not be common practice any more, as regulations now stipulate the maximum power (combination of IC engine and electric motor power at any time) and the maximum amount of energy (coming from the fuel and the batteries, if present) per stint.

This should make races easier to follow, and reduce the edge hybrid cars had over IC-powered ones, especially in traffic, where driver-activated boost coming from the electric motor is a significant help.

The hybrids will still have the advantage of operating as all-wheel drive in certain situations, having their masses positioned more conveniently between the front and rear axles.

Powertrain and fuel

The maximum combined power a car can produce at any time is derived from the sum of what is measured at each driven wheel using driveshafts torque sensors. The regulations state a window in which this overall power can be adjusted, depending on BoP needs, either increasing or decreasing it by a certain amount.

The upper limit is set at 520kW for now, the lower at 480kW, with nominal maximum

The primary driver of LMH rules was to have a top-tier class where manufacturers could compete, while deploying much lower budgets than LMP1

power in the middle at 500kW. This target is provided in the form of a power curve, shown in **Figure 1**, and all cars' power output should stay below the target curve at all times.

The regulations leave freedom of choice regarding engine architecture, capacity and maximum rotational speed, as long as overall power produced remains below the target.

Interestingly, there is a minimum engine weight of 165kg, and a minimum c of g height of 220mm above the reference plane. A similar approach is used for the gearbox, which must weigh at least 75kg and have a centre of mass no less than 150mm above the reference plane.

The electric power system can only apply positive torque to the front wheels out of the pit lane, with a maximum overall power output of 200kW.

At time of writing, the electric power can be applied to the front wheels only above 120km/h in dry conditions and between 140 and 160km/h in wet conditions (the exact speed is yet to be defined).

Concerning fuel tank capacity, the rules seem only to mandate a minimum volume to allow the car to cover at least 12 laps of the Le Mans circuit, plus the out lap and in lap.

Based on the energy required to complete a lap of the Circuit de La Sarthe (calculated using simulation) and considering petrol energy content and an engine efficiency of 40 per cent, the author came to a fuel tank volume of about 90l, which seems to match Toyota's press information.

The Alpine A430 (no. 36) runs heavier than last year's car at the limit of its homologation per the crash testing criteria, but with less power and so is able to use Michelin's 2020 tyre to good effect

Coasting should not be common practice any more, as regulations now stipulate the maximum power… and the maximum amount of energy per stint

As no minimum capacity is prescribed, this rewards engine designs that produce the target power most efficiently, thereby keeping fuel consumption lower. That said, there is still a given amount of energy per stint that teams have to respect. That covers the combination of propulsion forces produced by the electric and IC engines.

Tyre usage

An interesting difference, compared to the approach used for LMP1 rules, regards tyres.

As the non-hybrid LMP1 cars were added to the WEC grid in 2018, after Porsche left the championship in 2017, the FIA / ACO had the difficult task of balancing two different powertrain concepts. They tried to achieve this by allowing more freedom to the non-hybrid cars in certain areas to compensate for the absence of an electric motor, and the operation and development being carried out by privateers with much smaller budgets than the manufacturers.

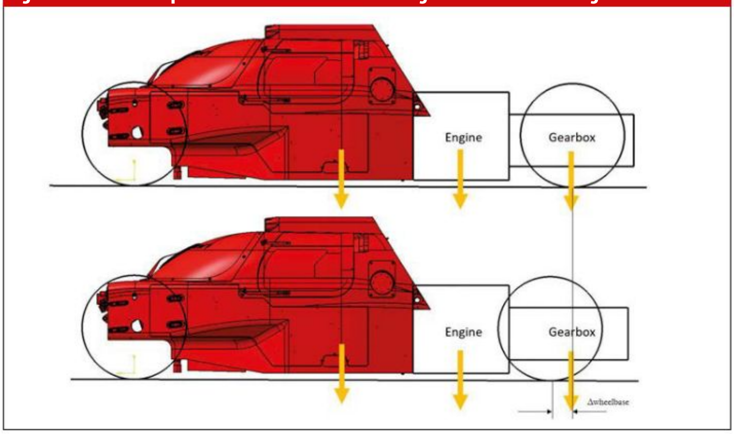
Besides the advantages offered by the hybrid system itself, hybrids had an edge over the rest of the field because they can use their tyres better, having the front wheels driven. Moreover, because of the positioning of the electric motor at the front, hybrids have a more forward-biased weight distribution, which helps them warm the four same dimension tyres more homogenously, and stress them more equally.

The non-hybrid LMP1 cars, on the other hand, were derived from LMP2s, such as the Oreca 07 or Dallara P217 chassis, though the rules mandated a 100mm shorter maximum length. Since the monocoque remained the same, this length reduction was mainly achieved by reducing the distance between the rear wheels and the tail end of the monocoque. That produced a shorter wheelbase and a less optimal, more rearward-biased weight distribution than the original cars, and the hybrids.

This is illustrated very basically in **Figure 2**. The weight forces of each main component of the car act closer to the rear wheel centre compared to a longer wheelbase solution with the main components remaining in the same position.

All of this meant the non-hybrid teams had issues coping with rear tyres stress and

Figure 2: Schematic explanation of the effects of reducing the wheelbase on weight distribution



deterioration, while at the same time not bringing front tyres up to temperature.

In 2021, on the other hand, the only tyre manufacturer (Michelin) for the LMH class will provide different specifications, depending on each car's characteristics. The rules allow two options for tyre dimensions, one where both front and rear tyres are the same, the logical choice for a part-time, all-wheel driven hybrid. The other option sees the front tyres smaller than the rears, which seems to be the logical choice for a rear-wheel driven non-hybrid, where all the traction stress goes into the rear tyres. Like the non-hybrid LMP1, rear-wheel driven only should have a better mass distribution.

Figure 3 shows a table extracted from the rules that summarises these two options.

It is reasonable to assume that, besides their dimensions, Michelin will use different tyre compounds and construction for various cars, as the performance requirements, and safety considerations, will conceivably be pretty different.

Aerodynamics

Aerodynamics is the area where the rule set made publicly available by the FIA provides the least information. Some aspects are described accurately, but a great many others are left to interpretation. The general approach seems to be to leave

Figure 3: Tyre dimension options *Source: 2021 LMH technical regulations*

	Option 1		Option 2	
	F	R	F	R
Tyre dimension	31/71-18	31/71-18	29/71-18	34/71-18
Max. complete wheel width	14in	14in	13.5in	15in

Figure 4: An example aero map. CAA is representative of downforce, CxA of drag force and Balance of the downforce distribution between front and rear axle

CzA

Frh\Rrh	14	20	25	31	45
6	3.42				
11		3.35			
15			3.36	3.43	
22					3.02

CxA

Frh\Rrh	14	20	25	31	45
6	0.771				
11		0.750			
15			0.761	0.771	
22					0.771

Balance

Frh\Rrh	14	20	25	31	45
6	0.436				
11		0.440			
15			0.434	0.449	
22					0.446

It looks likely that the regulators will apply an average to measured aero maps, according to a given procedure, to define the values of downforce and drag that will then be compared to the targets

The Toyota GR010 is in its first year and not yet technically perfect. Next year it will face Peugeot, and in 2023 Ferrari, as well as the LMDh cars from BMW, Audi and Porsche, plus potentially GM, Lamborghini and Acura, too

The Glickenhaus made its FIA WEC debut at Portimao in June after months of testing, mainly in Italy close to Podium who built the car. A crash and subsequent change of clutch cost an hour in the pit

it to the manufacturers, allowing them relatively big conceptual freedom. For example, the rear diffuser design is free.

Though it is unknown to this author if other areas are more tightly regulated, it seems logical to allow more freedom in terms of aerodynamics to incorporate brand styling cues into the design, which was one of the goals of the new rule set.

The way the rules are set that should be easy to achieve, with the most important performance parameters, like the amount of downforce and drag, remaining inside some tight, defined boundaries.

Certainly, the two existing LMH cars (Toyota GR010 and Glickenhaus LMH 007) have different approaches to the aerodynamic areas, particularly the rear diffuser and rear wing.

The publicly available technical regulations contain none of the critical aerodynamic targets, though what has been communicated to the media in the last few months suggests the cars must achieve an aerodynamic efficiency of about 4.0.

Aerodynamic efficiency is defined as the ratio between downforce (the aerodynamic force pushing the car down at speed) and drag (the aerodynamic force braking the car at speed). The author understands from other sources that a later iteration of the rules should have this target slightly above 4.0. Despite this, there are some very important open points.

The general approach seems to be to leave [aerodynamics] to the manufacturers, allowing them relatively big conceptual freedom

Aero measurement

The first is how the ACO will measure aerodynamic performance. It will evaluate the LMH cars in the Sauber full-scale wind tunnel, but some engineers are concerned about this tunnel's accuracy, which could be limited with a full-scale car due to blockage effects.

It seems clear the LMDh (IMSA top class) cars, which will be allowed to compete in WEC in the next few years, will be tested in another wind tunnel. Using different tunnels could in itself be a source of misalignment.

Stating the cars will have an efficiency equal to about 4.0 doesn't say much because both downforce and drag change significantly depending on parameters like front and rear ride heights, roll, yaw, steering and wing angles.

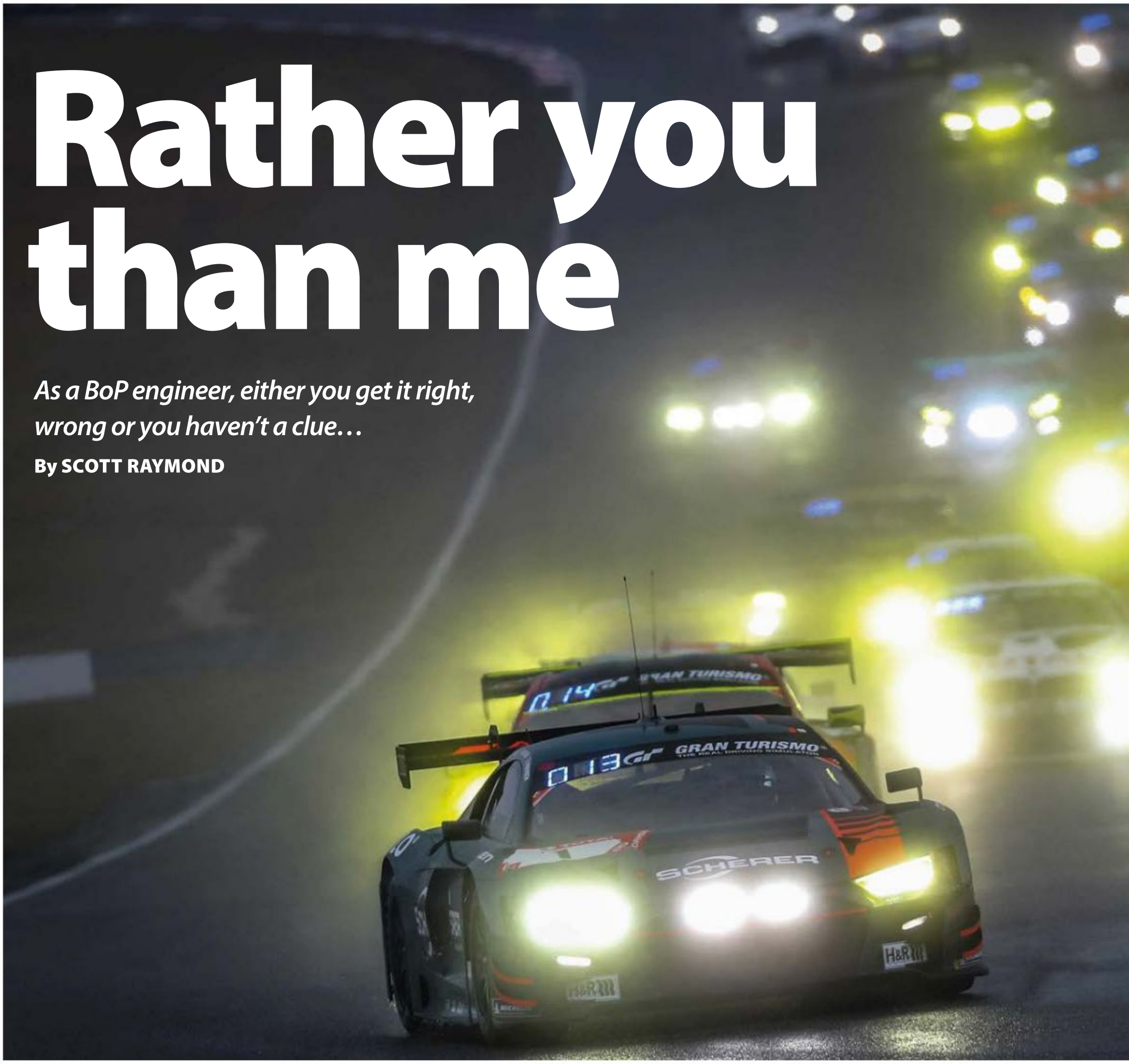
All this data is normally collected in an aero map, which is a table where downforce, drag and how downforce is distributed between the front and rear axle is noted. Inputs include different front and rear ride heights, while keeping other important settings, like wing angles, constant.

Figure 4 shows an example of an aero map. Here CAA and CxA are meant as the non-dimensional downforce and drag coefficients, respectively, multiplied by the frontal area. At the same time, Balance indicates the portion of overall downforce acting on the front axle.

It looks likely that the regulators will apply an average to measured aero maps, according to a given procedure, to define the values of downforce and drag that will then be compared to the targets. If the author's information is correct, this process will use a weighted average over the whole aero map, with more weight being given to certain conditions that are more critical for performance and specific criteria to guarantee aerodynamic stability and safety.

It is also understood that the regulations set an upper and lower limit to the amount of downforce the cars can produce in every homologated configuration (wing angles, for example). This area will be analysed in more detail in next month's instalment, in an attempt to better understand its effects on performance.

We will also perform a more in-depth analysis of the expected performance of the new cars, using lap time simulation to quantify how fast LMH vehicles *should* be at Le Mans.



Rather you than me

As a BoP engineer, either you get it right, wrong or you haven't a clue…

By SCOTT RAYMOND

Have you ever wondered what it is actually like to be a Balance of Performance (BoP) engineer for a racing series? How about being a BoP engineer during the most important race of the year for that racing series? Well, now is your chance to find out, because what follows is a real-time account of my experiences as a member of the BoP Technical Committee leading up to and during the 2021 Nürburgring 24h race event.

For the past four years, I have been working as a member of the Nürburgring 24h Technical Committee. This committee falls under the umbrella of the ADAC Nordrhein, which is the organising body in charge of the Nürburgring 24h race.

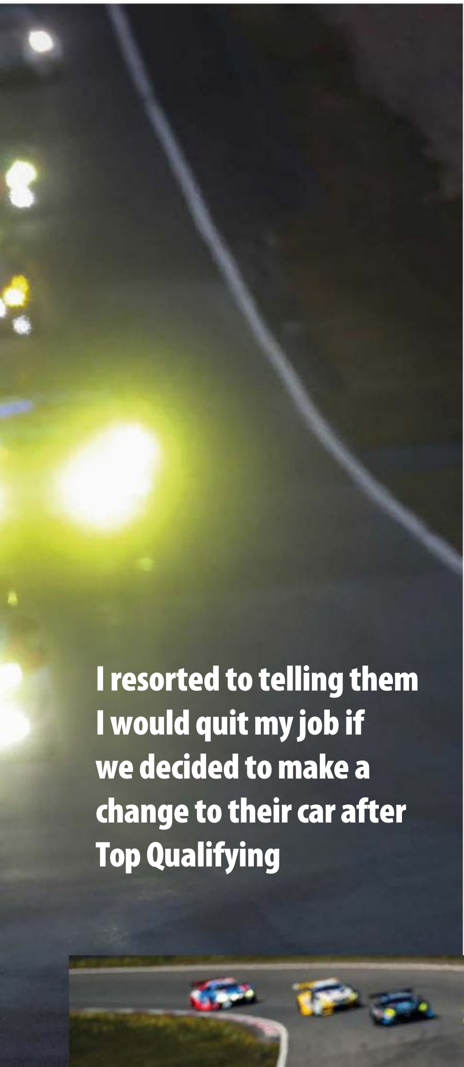
In this time I have been privileged to work alongside several world-class individuals, including Norbert Kreyer, Mike Gramke, Walter Hornung, Mirco Hansen, Rafael Tomaszko and Silvia Bethold. The latter deserves a special mention as she is retiring this year after 34 years with the ADAC Nordrhein. I'm going to miss her smiling face at next year's race.

GT3 BoP

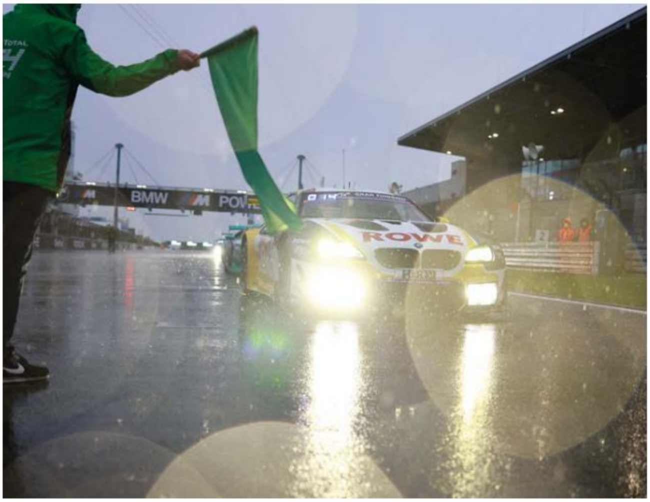
The Nürburgring 24h race is not truly part of a racing series, but it is heavily intertwined with the NLS (Nürburgring Langstrecken-Serie) in that the NLS uses the BoP tables for the GT3 cars as defined by the Nürburgring 24h Technical Committee. There are usually two to three NLS races that take place before the Nürburgring 24h Qualifying Race, which is a six-hour prelude taking place three to four weeks before the main event. NLS races are generally four hours long, so they are true tests of endurance themselves.

Of course, all these races take place at the gruelling Nürburgring, where parts of the grand prix circuit are used in conjunction with the entire Nordschleife circuit. The circuit for the Nürburgring 24h covers a distance of over 25km, with GT3 cars able to complete a single lap in qualifying trim in under 8 minutes and 10 seconds.

Now, without further ado, let's step into the shoes of a BoP engineer in the days leading up to the race event.



I resorted to telling them I would quit my job if we decided to make a change to their car after Top Qualifying



The elements play their part, too. Heavy rain and fog affected the race this year, leading to a long overnight stoppage

T minus 10 days

It is Wednesday, 26 May and we have just released the BoP tables for the 2021 Nürburgring 24h race.

I find myself reflecting on how we, the Technical Committee, arrived at this point. To truly appreciate this, we have to go back to the 2020 edition of the race during late September last year.

With the Covid pandemic wreaking havoc on the motorsports industry, we have been fortunate to run five NLS races leading up to the 24h race. We (the BoP Committee) have done the best job we can with the data available but, as is typically the case, there are still some open questions about the true performance of some of the vehicles. Porsche Motorsport introduced its 2020 EVO of the 911 GT3 R, but has been nowhere relative to the other cars for the entire season. We have therefore tried to bring its performance level into the fold with a pretty large mass reduction.

Unfortunately, weather played a significant role in the performance demonstrated by each of the cars. It has rained almost non-stop for the past several days and, frustratingly, the rain didn't let up over the course of the 24h race. In fact, the race had to be red flagged overnight when conditions became too treacherous.

In other BoP bad news, the fastest Ferrari experienced serious performance issues on its rain tyres, so we have no idea where it stands.

At this point I am extremely disappointed that none of our outstanding questions were answered. We will go into 2021 with several unknowns remaining.

Fast forward to 2021 then.

The performance of the Porsche was unknown after the 2020 race due to adverse weather, so going into 2021 it was still an unknown

2021 NLS Race 1

Snow. Race cancelled. Not a great start.

2021 NLS Races 2 and 3

Thankfully, the weather has started to co-operate, and we have seen some quality lap times by all manufacturers. We have also obtained a lot of great data for all cars that has been fed through our analyses.

The manufacturers appear to be taking different strategic approaches in the lead up to the 24h race. Some have shown up in force with several cars and full factory driver line ups, while others only have customer cars piloted by non-factory drivers. This adds uncertainty about the ultimate performance capability of some of the cars.

2021 24h Qualifying Race

It's a similar story to the NLS races, with some manufacturers not bringing factory drivers, or customer cars outperforming factory cars. I hope this doesn't negatively affect the BoP for the 24h race.

The only change we have deemed necessary following the Qualifying Race is an increase in power level for the Ferrari. With its EVO package, the car appears to have more drag than last year, so an increase in power will make it more competitive on top speed and improve its ability to pass slower cars.

At this point it is still 10 days before the 24h race. The BoP table we released has some TBD values for Ferrari engine power. Our plan is to test several boost levels on the engine dyno during the week before the race and then decide what new power level to prescribe the Ferrari.

The Qualifying Race still left some question marks over the engine power of the Ferrari, and dyno testing was required

T minus 9.9 days

Well, that didn't take long. We have already received an angry email from one of the manufacturers, dissatisfied with the BoP tables. Still, at least it's only one.

Perhaps the days leading up to the race will be relatively relaxed, and I'll be able to build up some energy to tackle the challenge ahead. In cinematography, that statement would be referred to as foreshadowing!

T minus 8 days

Over the past year and a half, I have taken up mountain biking as a hobby, so find myself out on the trail near my house clearing my head. On most days I ride, I have a moment of clarity about five minutes into the ride, which gives me over an hour to work on that idea while I pound my way through the Florida forest trying not to fall on my head.

With mountain biking now such an integral part of my daily routine, I bring my bike with me to Germany, hopeful I will be able to fit in the odd ride when the stress levels get too high, or when I need to mull over a new idea.

Later that day, I make the mistake of looking at the long-term weather forecast for the Nürburgring. Rain, rain and more rain. I am now desperately hoping we do not have a repeat of the 2020 race.

T minus 7 days

It is Saturday, 29 May and today's agenda includes a Covid test, packing my bags and beginning the journey from Daytona Beach to Germany. My bike is packed in its travel case.

T minus 6 days

I touch down in Frankfurt on the morning of Sunday, 30 May, and the weather is gorgeous – nothing like what is forecast for race day.

On the drive to my hotel near the Nürburgring, I pass an area of the circuit called Pflanzgarten, and both the road and parking area are packed. There must be another racing event going on, but I have no idea what. I think I see a Sprinter van driving next to a Porsche.

That evening I go for a bike ride, resolving not to think about BoP until Tuesday.

T minus 5 days

Monday, 31 May and I have a chance to speak with Mirco Hansen, so ask him what was going on at the track yesterday. He replies, 'Tourist drives.' Wow! This really puts the popularity of this track into perspective for me. I've always held it in a special place in my heart, but it's amazing to see how many other people feel the same way.

To add to that perspective, there are four separate villages within the boundary of the Nordschleife. I marvel at just how impressive this circuit really is.

The weather is still beautiful. The forecast is not. I go for a bike ride.

T minus 4 days

Tuesday, 1 June 2021. Today is the first official day at the Nürburgring. The Ferrari has now been on the engine dyno, so we are working towards finalising what power level we need to set for it. Our general feeling is the car needs a speed increase of +3kmh, which requires an additional 12-15bhp.

We have a meeting this afternoon with representatives from the only manufacturer that has currently voiced discontent with the published BoP tables. This manufacturer feels we have not addressed an apparent lack of top speed for its car. We have not seen any historical data to support this claim, but have promised to do a thorough review of the historical speed data from the past two seasons, just to be sure.

Any big data analysis project like this falls squarely on my shoulders, so I have been working like mad to come up with a method to visualise the historical speed trends. The circuit has a total of eight speed traps that have been placed in strategic positions to capture different dynamics of vehicle performance. I have data going back to the 2019 24h Qualifying Race. This is no small task.

Oh, and to top things off, the weather forecast for race day is still rubbish.

T minus 3 days

I'm now not sure what day it is, but today was insanely busy. After making good progress last night, I spend most of the day working on the historical analysis of sector speeds.

We are also visited by every manufacturer representative today and have spoken to each one at great length. It's been one of those days where you have a really important task to finish, but everyone and their brother wants to discuss other, less pressing issues.

Despite this, I manage to come up with something that tells a great story about the relative performance levels of the cars in terms of trap speeds. **Figure 1** shows the historical trend in the speed measurements taken at the end of the longest straight on the Nürburgring. For each manufacturer, the weighted average speed measurements for the two fastest cars (in terms of lap time performance) are presented. A smoothing line is fit through the data points, and a coloured band is used to indicate the range in performance. It should be noted that all of the data that went into creating this graph has been filtered to remove any significant tows ie artificial increases in speed resulting from following a leading car.

After seeing this, the manufacturer that thought it had a speed deficit realises it does not, so a positive has come out of all this effort.

Figure 1: Historical speed trends taken at the end of the longest straight on the Nürburgring

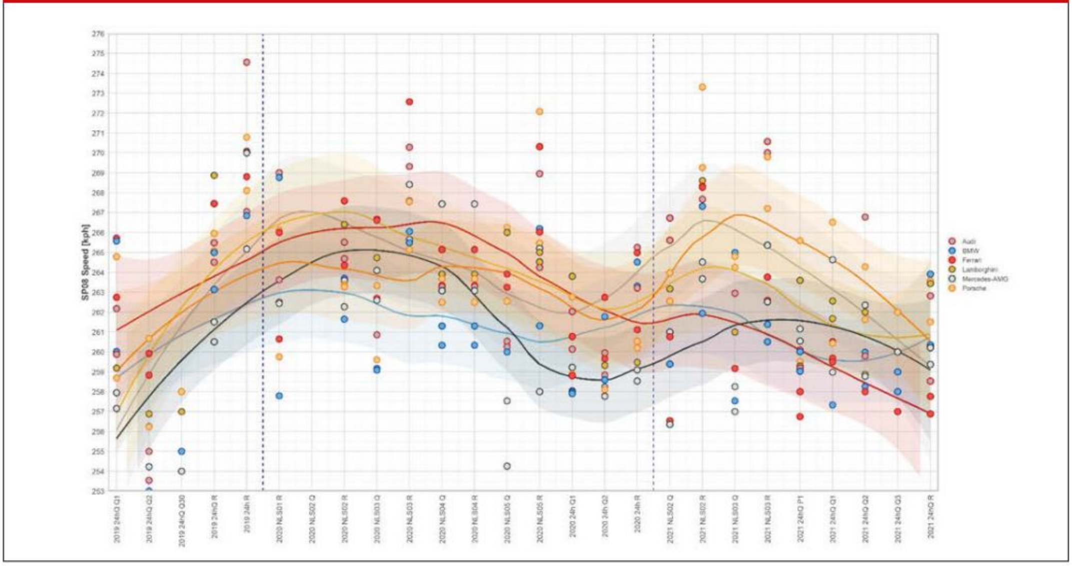
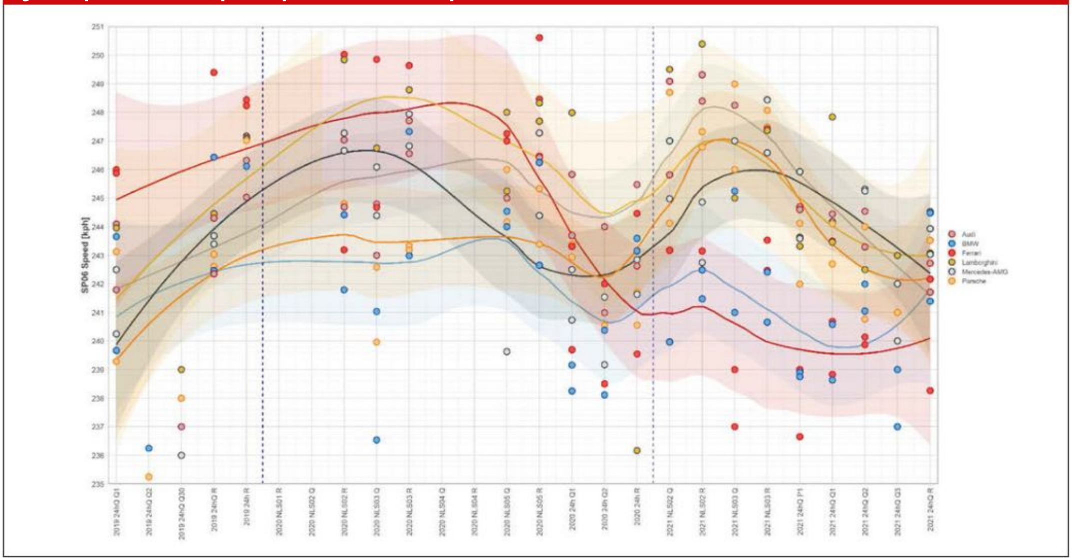


Figure 2: Speed trends from speed trap SP06, located on an uphill section of the track between Kesselchen and Klosteral



You can also clearly see in **Figure 1** that the Ferrari is lacking top speed relative to the other cars, so this provides an additional data point supporting our decision to increase the Ferrari's power level. However, we notice a couple more issues we now need to address.

The first arose when we started looking at the speed trends from SP06, which is a speed trap located on an uphill section of the track between Kesselchen and Klostertal. The part of the circuit that leads up to this speed trap starts with the cars driving over a bridge that crosses over the village of Adenau, the lowest elevation point on the circuit. The cars turn through Ex-Mühle and climb about 25m vertically to the Bergwerk corner. From there, it is another 90+m uphill to the speed trap.

In **Figure 2** you can see that both BMW and Ferrari have a disadvantage at this point on the circuit. We are already working to increase the power level of the Ferrari, but it's clear we also need to look at increasing the power level of the BMW as well to help it be competitive in this section of the track. The power increases for both cars will also help them negotiate traffic better, which will make them more competitive over the duration of the race. We decide to make a small reduction in mass for the BMW to help it further with this characteristic.

A second issue we discover is the Audi appears to lack low-speed acceleration. I cannot share the graph that demonstrates this, but the evidence points to increasing the power level for the Audi as well. The problem here is we don't want to reduce the Audi's lap time by the amount that will come from an increase in power, so we decide to increase its mass as well so the lap time change will be neutral.

The main challenge we face right now, though, is that it is very late in the day on Wednesday and, before we can publish any BoP revisions, we need to discuss the proposed changes with all the manufacturers. In short, we are not going to get this published tonight.

T minus 2 days

It is now Thursday, 3 June and there are now just two days until the race. On-track action starts today, and we have a couple of BoP changes we want to finalise before the cars run on track.

I try to wake up early and go for a bike ride to clear my head but fail. My torturous checking of the weather forecast is not revealing any positive news.

T minus 51 hours

Qualifying 1 started at 12.30pm and runs until 2.00pm. We were unable to publish any BoP changes before the session began because we were meeting with manufacturers right up to the last minute. In some of those meetings, I felt more like a punching bag than anything else. The proposed changes impact the lap times of the cars by less than 0.1 per cent, yet some of the manufacturer representatives act like we are creating a disaster. I get it, it's the biggest race of the year, and no one wants to give up anything to their competitors, but they still have to understand our decisions are based strictly on data and the desire to ensure all cars have an equal opportunity to win the race.

The lap times from Qualifying 1 are dismal. No one wants to go fast. Everyone has at least seven seconds in the bag. As a result, the data from this session is pretty much useless.

T minus 43 hours

Qualifying 2 started at 8.30pm and goes until 11.30pm. Everyone is running through their programmes, but still no one is going very fast. It is the night session, and most teams want to make sure all the drivers get a chance to drive in the dark.

T minus 40 hours

11.30pm and Qualifying 2 is over now. I am waiting for the vehicle data so I can post-process everything, but know it's largely useless as we've still not seen any good performances from any of the cars.

We spent a good portion of the session discussing and finalising the BoP changes through the proper channels and now have the approval we need to publish, though we still have to meet with one last manufacturer to get the final sign off.

At 12.15am, we finish the meeting with the last of the manufacturers. I am not going to bed until the revised BoP tables are published.

T minus 1 day

Friday, 4 June and on-track activity doesn't start today until 3.30pm, so I go for a bike ride, unleashing at least some of the stress that has accumulated over the past couple of days.

T minus 25 hours

I've now reached my limit, I've had enough. I've spent the last few hours in intense discussions with manufacturer representatives over the changes we published late last night. The conversations were going absolutely nowhere and just kept circling back to the same thing.

I kept reminding them that the lap time change for Audi was neutral and the BMW was 0.1 per cent. Finally, in frustration, I said, 'This is going nowhere. Why are you here? What do you want?' Their response was they felt their car should be 15kg lighter. I simply said, 'No. If there was evidence indicating your car's mass needed to be reduced by 15kg we would have already done that.' That meeting ended soon after.

Another manufacturer was concerned we would peg them back after Top Qualifying, feeling that if they went out with a qualifying set-up on the car and went fast, we would increase their mass, or reduce their power. They wouldn't take my word that we would not change their car, regardless of the outcome, so I resorted to telling them I would quit my job if we decided to make a change to their car after Top Qualifying. Now I really need to go for a bike ride.

Our decisions are based strictly on data and the desire to ensure all cars have an equal opportunity to win the race

T minus 24 hours

3.30pm on Friday, 4 June, time for Qualifying 3. The weather is cooperating, so I'm hopeful we'll see some good performances.

In a last lap effort, the no.19 Konrad Motorsport Lamborghini pulled an 8:15.225 out of the bag to go 3.350 seconds faster than the second-place car. I'm hopeful that will wake up a few of the other manufacturers and teams.

T minus 21 hours

6.30pm and Top Qualifying 1 is about to start. The top four finishers in this session will advance to Top Qualifying 2 and join the cars that have already earned a position in that session. The sky to the east is black, and lightning is streaking across the sky. I hope we can get all the way through both parts of Top Qualifying without any rain.

Phew! TQ1 finishes just as the rain starts.

It then continues to rain for all of TQ2. The disappointing part of this is we expected to see the ultimate performance from each of the cars entered in this session as they fought for pole position. While I don't feel quite like we haven't a clue, I sure would have liked to get some good data at this point to validate where we are.

Konrad Motorsport Lamborghini went some way to silencing the critics after Qualifying 3, finally showing what the car is capable of

The start of a truncated 24-hour race with rain lingering in the air, a damp track and grumpy teams up and down the pit lane. On the upside, the published BoP tables appear to be satisfactory

But, in the department of very good now, there will be no BoP changes following Top Qualifying. I don't have to quit my job.

Race day

It is now Saturday, 5 June and the race starts today at 3.30pm. I spend the time before the race wandering through the starting grid, genuinely excited about the race ahead, trying to ignore the few rain drops I feel while out on track.

The forecast for the race has remarkably improved, though things look questionable at the start of the race and, due to all the rain we've had in the past 24 hours, the track is not exactly dry.

T plus zero seconds

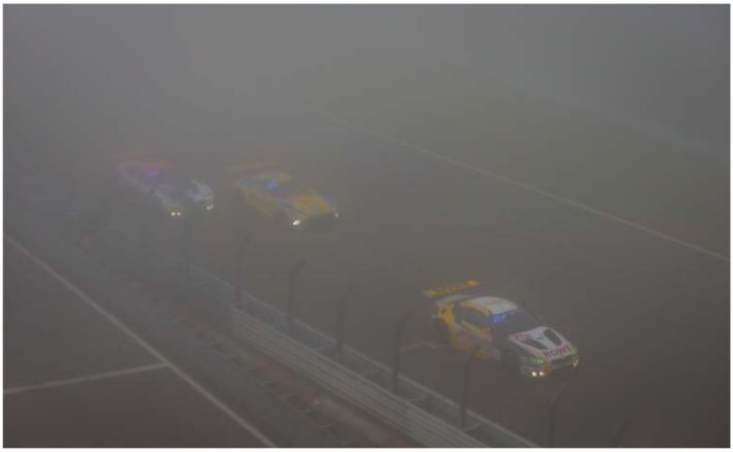
Green flag! Our fate is sealed now. All we can do is watch the race and see how it all unfolds.

T plus 18 minutes

We are watching the live stream of the race and see two cars from one manufacturer motor past one car from another manufacturer on the Döttinger Höhe – a long straight where cars are at full throttle for over 2.7km. I take note of the speed traps at the beginning and end of the straight because I expect to have to defend what we just witnessed on TV. I also remind myself that a two-car tow is exceptionally strong, though I have no idea what wing angles the cars are running and we only saw the straight, so we

Rain is not the only thing that affects the BoP process, manufacturers sandbagging makes it difficult to gain meaningful data

While the race is on, the BoP Committee watches intently, noting speeds through the many speed traps for apparent inconsistencies



Visibility is key and, when a right old pea souper of fog sets in, organisers had no option but to call a halt to procedings

Porsche took victory once again, the Manthey team taking its seventh win, this time in its 25th year in motorsport competition

I'm happy to report we can probably strike 'haven't a clue' off the list

have no idea what happened coming out of the corner. Did the lead car have a poor corner exit? What tyres are the cars on? Did one gamble on rain and is running intermediates?

This example illustrates how important it is to gather all the facts, and fully understand the situation, when looking at specific events related to Balance of Performance.

T plus 19 minutes

The head of motorsport for the manufacturer of the car we just watched being passed just texted. Paraphrasing, he basically said, 'See, I told you that car would have too much power.'

Later on, the same car would be leading the race by a decent margin.

T plus 6 hours

The race has been red flagged due to fog. The Nordschliefe is a cruel mistress. While she has given us a relatively dry race so far, she now makes it impossible for the flag marshals to see their next colleague on the track. The situation is too unsafe to continue racing.

The leaderboard is a good mix of different manufacturer cars at this point. The lap times are not there yet because of the drying track, fog and local yellows. I'm going to bed.

T plus 16 hours

I am back at the track and the fog is still pretty thick. I'm not sure when we will go green.

T plus 20 hours 10 minutes

The fog has lifted. We are finally back racing, and the track is dry, so we should see some quality laps by everyone.

T plus 24 hours 04 minutes and 12 seconds

Chequered flag! After an abbreviated 24-hour race, we find four different manufacturers in the top five cars, seven cars separated by less than one minute and nine cars still on the lead lap. The theoretical lap times from timing show the cars to be quite balanced, but each car really only had the opportunity to put in eight or nine good laps.

I cannot pass final judgement until after I've post-processed all the vehicle data, but at this point I think it fair to say we are leaning more towards getting it right than getting it wrong. Better than that, I'm happy to report we can probably strike 'haven't a clue' off the list.

Phew! I'm going for a bike ride.

Suspended reality

KW Automotive developed its latest five-way adjustable damper specifically for the Nürburgring 24 hours, and it was on the winning Porsche entered by Olaf Manthey

By RACECAR STAFF

The always demanding Nürburgring offers a unique challenge to suspension manufacturers, and it's one KW Automotive relishes

Gruppe C

Setting up a car for the rigours of the Nürburgring 24 hours is one of motor racing's great challenges. Suspension company, KW Automotive, worked hard to develop a five-way damper that has given teams such as Porsche and BMW set-up options that were previously unavailable on their GT3 cars.

Although the 24-hour race was shortened by rain and fog this year, car set-up was crucial for the sprint to the flag, and performed well enough on Olaf Manthey's 25th anniversary at the 'Ring for him to take victory.

'We just launched a new specification for the Manthey car and that will be a future GT3 damper, which will also be on the BMW M4 GT3,' confirmed Thomas Rechenberg, head of motorsport at KW Automotive.

'We have built from a single adjustment to a five-way adjustment, and developed it on the seven-post rig with the Manthey car. The damper has a cartridge system, so basically we are benchmarking against Öhlins and Multimatic, looking at what they are doing now, seeing how we can put strength into our modern system.'

The damper is an update to the company's four-way damper that was introduced in 2017 and campaigned successfully at the 'Ring in the VLN series (now called the NLS). From the extensions seen over brows of hills to the compressions in dips, plus aggressive kerbs and changes in track surface, the Nürburgring is a uniquely demanding circuit, and suspension development is key to good lap times and traffic management.

'What we learned from our four-way damper is to have a really short valve opening time, and so the opening time is extremely short with our new product,' says Rechenberg. 'On the Nürburgring you need to have a short valve opening because if it is too long you have two choices – no grip because your valve is too often closed, or your car bottoming out because it is always open.'

All ways ahead

While the five-way damper is the gold standard in the range, KW continues to offer two, three and four-way dampers for competitors in the 24-hour race.

'The two-way damper is pretty easy, solid damping technology with no reservoir, so is affordable to small teams in the RCN or GLP, but for the NLS and the Nürburgring 24 hours, we are always providing the five or three-way adjustable dampers,' says Rechenberg.

Development has been ongoing on the seven-post rig with both Porsche and BMW in preparation for the season, and KW found it was going softer on spring settings than expected. That gives the cars flexibility to run off line, a key point to racing in a multi-class formula where cars regularly overtake in traffic.

The new five-way adjustable damper is a development of KW's previous four-way unit, and has been developed on the company's seven-post rig with both Porsche and BMW

KW Automotive

For the Nürburgring 24 hours this year, KW Automotive supplied 61 cars, around 50 per cent of the grid

KW Automotive

The range of KW Automotive dampers for entry level and top class GT racing, offering different adjustment possibilities according to choice of damper

It also gives the teams better options in adverse weather conditions. 'If you are driving a single lap in super pole and you are on the line, then everyone is quick,' says Rechenberg. 'As soon as you leave the line to overtake, though, other cars were completely lost.'

Being able to manage the kerbs is always a key to surviving the 24 hours, as often cars will have to run over them to avoid contact with other cars, while minor mistakes can be heavily punished by the nature of the track.

'You build a car that is basically half rally because sometimes you have to cut through the grass,' notes Rechenberg. 'We were thinking that maybe we also needed to fit hydraulic bumpstops into the road course damper because we think that it is necessary.'

Softly softly

Setting the cars up at the ride height required for the Nürburgring is also a challenge for the GT3 teams, with a minimum ride height of 70mm specified, far higher than other circuits. In this case, it is preferable to have a softer spring that will sit the car down under load. For example, at full speed on the Dottinger Hohe, which will then help to reduce drag.

'For us, it is definitely a very difficult story,' admits Rechenberg. 'Our development advantage, what we might be working with, can be taken away when you get a smaller restrictor, or more weight, because of our top speed. On the other hand, we always have to work with an homologated car, and if you stop developing then you are definitely not competitive any more.

'These soft springs give the option to drive dynamically lower, which gives you better downforce, less drag and therefore more top speed. You enter the NLS 1 or NLS 2 and they see that the Porsche has gained top speed, and they wonder where that is coming from. You then receive more weight and a smaller restrictor [from the BoP engineers] but, basically, you have to work like this.'

Having such changes in set-up creates a huge problem for the engineers managing the Balance of Performance too as their job is to look at the physics and try to come up with a fair system, but they can only go so far into the data for each car.

'The BoP is now a bit blind,' says Rechenberg. 'If they are working on tyre wear, and you give the car a set-up that allows it to work off line without compromising tyre wear, how is that going to be judged by Balance of Performance? You can obviously have a good lap, but also be quick over a stint.

'Then you have other manufacturers who are able to do one quick lap in the race, and then see their pace dramatically fall off. That is making the whole process harder to handle.'

One of the keys to understanding suspension set-up is, of course, to have data from multiple cars, and for the Nürburging 24 hours this year, KW supplied 61 cars, around 50 per cent of the grid. Not all of them were in SP9, and not all of them featured the latest damper technology, but all were equally as important to the company.

'GT4 is probably a more important category for us,' admits Rechenberg. 'We will do the next [BMW] M4 GT4, and we have done all the AMG GT cars, apart from the Toyota and the Porsche, so we don't want to lose ground there, either.'

Development is allowed in the SP9 class at the Nürburging and, with BMW's M4 testing at Spa mid-June, more data has been gathered to help with the set-up sheets that will be available to Porsche and BMW customers under the new homologation. Under current rules, dampers are homologated into GT3 by the manufacturers with no option to change mid-cycle, which means race data is harder to come by other than open test days or open technical regulations.

Prototypes ahead

However, the company has also its sights set on slightly different targets. Having secured the GT3 win at the Nürburgring, and also partnered with BMW, KW is also looking at the new Hypercar and LMDh rules with a view to supplying one of the chassis manufacturers and OEMs that are interested. It won't be Porsche or Audi as the VAG companies have signed with Multimatic and so will use its suspension technology, but Rechenberg is confident KW will be on the grid in Prototypes at Le Mans.

'We are in good contact with one of the chassis manufacturers, and one of the manufacturers,' he says. 'I think the possibility to end up in one of the projects is quite high, and it is still open from the rule side whether or not the damper will be a manufacturer part or a chassis design part. The Americans are favouring the cost side that the dampers are part of the chassis design, but the ACO wants to give manufacturers a little bit of freedom, but that is something that is not yet decided.'

What is likely is that GT3 will be at Le Mans in 2024 at the latest, and that puts KW Automotive on the grid at the world's most famous endurance race with cars that will be capable of securing class wins. The development work that continues to be done on the Nürburgring will certainly put KW in good stead for that eventuality.

XPB

A word in your Shell-like

Racecar investigates the highly complex world of Formula 1 fuels and lubricants

By STEWART MITCHELL

The evolution of fuels and lubricants in Formula 1 is one of the most critical and untold stories of the sport in the current era. The introduction of the hybrid regulations in 2014 changed the engineering formula for the internal combustion powertrain from an air-limited, mechanically-restricted formula to an energy-limited one.

This shift in concept altered the engineering approach, and set the road map to the world's most efficient race powertrains, now producing over 1000bhp from the combination of 1.6-litre, turbocharged V6 internal combustion engine (ICE) and energy recovery system (ERS) at a thermal efficiency of over 50 per cent.

For the current turbocharged V6 formula, the restricting element is no longer the oxidising component of the combustion, it is the hydrocarbon element. This forces engineers to think completely differently about the whole process of combustion.

The absolute power of the engine derives from its ability to transfer the joules of energy stored in chemical form into kinetic energy. The challenge is to adapt the air-to-fuel ratio and combustion parameters to extract the most energy out of each fuel droplet, rather than simply adding more.

The number of joules of energy entering a contemporary F1 engine can be considered a constant as the regulations fix a fuel mass flow rate of 100kg/h. The ratio of energy entering the engine in fuel form to that turned into useable kinetic energy is the primary target for the fuel engineers.

'The 50 per cent plus thermal efficiency of the current crop of Formula 1 engines is extremely impressive, and most of that is attributed to the mechanical design of the engines,' explains Benoit Poulet, Formula 1 fuel development manager and trackside team leader at Shell. 'However, the fuel contributes 25 per cent of the functional thermal efficiency of the engine.

'Of course, the engines were not at 50 per cent thermal efficiency on day one of these regulations in 2014, so this journey has been ongoing for the last seven years.'

Fuel evolution

The limiting factor of the naturally aspirated, fixed displacement, air-limited engines was how high the engine could rev, which is a function of their combustion speed

‘Engineers set about developing the fuel chemistry to go through the combustion process as fast as possible’

Benoit Poulet, Formula 1 fuel development manager and trackside team leader at Shell

Ferrari’s SF21 FIA Formula 1 World Championship contender features no fewer than seven products from its principal partner, Shell, helping it to work as efficiently as possible

and mechanical stress. There were two major elements of the fuel formulations for that era: they were designed to balance peak power output potential (as a function of calorific value and combustion speed) and fuel consumption. The use of each was track dependent.

In the hybrid era, the mass of fuel for the race is limited and the fuel flow is limited in mass at any given time. So, the mass becomes a fixed parameter. This takes out the track dependency as it was in the past. Engineers can also trade off kilograms of fuel carried against fuel consumption and peak power, as a function of the vehicle dynamics gains to be had from carrying less fuel at certain tracks.

'With the current hybrid regulations, which fix the fuel in mass, the track dependency is out,' notes Poulet. 'It is the same in Monaco as it is in Monza, and even going to Mexico as well if we also include the air pressure parameter. It doesn't change.

'However, although the fuel type trade-off no longer exists, you see another exchange in the current regulations set. Because the fuel flow and fuel load are prescribed in kilograms, there is scope for development of the calorific value of the fuel.

'When the energy-limited formula came into place and research into the fuel started, Shell discovered that some fuel molecules produce significantly more energy than others. The development targets then shifted to finding how engineers can apply as much energy into one kilogram of fuel and generate the proper pressure and motion for the direct injected gasoline engine.'

The research octane number (RON), which gives a ranking of how close to the most efficient moment the spark plug can ignite the fuel, is a primary driver in the combustion development of the high-efficiency fuel.

'In theory, you want all combustion to happen instantaneously at top dead centre (TDC),' highlights Poulet. 'Physics dictates that this cannot occur as combustion is a process that happens in stages. Despite this ideal being physically impossible to achieve, the engineers set about developing the fuel chemistry to go through the combustion process as fast as possible.'

Knock control

Because the current engines are turbocharged, there is a lot more motion and chaos in the combustion chamber than with the old naturally aspirated engines. So spontaneous combustion (aka knock) is a substantial limitation and consideration for contemporary Formula 1 race fuel blends.

Combustion chamber, piston crown and piston ring pack design are all critical in the mitigation of knock, which is why companies like Shell work so closely with their Formula 1 engine design squad partners at Scuderia Ferrari.

'With the energy that you get into one kilogram of fuel, how much you will be able to condition the fuel to combust completely and as close as possible to TDC, and how quickly it will happen, has changed dramatically since the start of the energy-limited formula began,' highlights Poulet.

'Additionally, despite the [15,000rpm] rev limit and the operating rpm of the current

Achieving efficient combustion in a fuel-limited formula pushes engineers to run the engines ever leaner, and drives technology such as pre-chamber ignition and the use of homogenous charge combustion ignition

Formula 1 engines being significantly lower than the previous naturally aspirated, air-limited formula [now operating at peak rpm around 12,500-13,000rpm], engineers want the pressure build up from combustion to happen even faster than before.

'When the piston starts to go down, the chamber volume increases, which means work is required to build the pressure inside the chamber until BDC.'

Efficient combustion

The combustion parameters are defined first before the mechanical geometry around it is configured. Achieving efficient combustion in a fuel-limited formula pushes engineers to run the engines ever leaner, and consequently drives technology such as pre-chamber ignition and the use of homogenous charge combustion ignition (HCCI).

XPB

Ferrari's SF21 is significantly better performing than its predecessor, the SF90, scoring a second place podium at the 2021 Monaco GP in the hands of Carlos Sainz jnr. Fuel for thought

XPB

Shell's bespoke racing fuels are designed to extract maximum efficiency from every molecule of fuel that goes into Ferrari's 1.6-litre, turbocharged, V6 Formula 1 race engines

'Every fuel molecule must meet the required amount of air to satisfy the peak efficiency in desired power regions of output,' says Poulet. 'Running the engine lean pushes the combustion into a more knock sensitive and unstable state as every non-stoichiometric event can disturb the ideal combustion.

'Hardware and fuel formulations produce the basis from where high performance, ultra-lean combustion science can prevail in an ultra-high load environment, such as that seen in contemporary Formula 1 powertrains. That is where our development of the fuel behaviour in a lean environment prevails. We now have stable, precise, lean and powerful combustion in all load cases.'

Calorific density optimisation is a huge part of the development of Formula 1 fuel because the only control parameters specified by F1 regarding fuel is the type and its weight in kg. Improving the calorific density of the fuel can yield substantial performance gains, as packaging the specified 110kg of fuel in a smaller volume will aid vehicle dynamics.

'Every fuel molecule must meet the required amount of air to satisfy the peak efficiency in desired power regions of output'

Benoit Poulet

When engineers look to increase the potential of a kilogramme of fuel there are trade-offs between the weight of molecules and their overall performance.

'Formula 1 tightly regulates the fuel constituents, like in the road car environment,' explains Poulet. 'The critical parameters of density, combustion speed and calorific value are thereby the nature of the prescribed compounds. Ninety nine per cent of the compounds found in the Shell Formula 1 fuel are also in its high-power road car fuels.

'Shell simulates various fuel densities to see how it affects engine performance in the Formula 1 operating window at the given load case. The higher density fuels we have found recently have enabled the 110kg of starting fuel load to package in less volume, allowing the chassis and aerodynamic teams to design a physically more efficient car.'

Mechanical elements

The Ferrari SF 21 engine is the co-optimisation / co-design effort of Ferrari's mechanical engineering team and Shell's fuel and lubrication team. Neither develops without coinciding with the other. When it comes to the piston crown, combustion chamber shape and the piston ring pack design, Shell wants to come with the capability to map the influence of the fuel, and *vice versa*, quickly.

For this, the company has developed significant digital combustion modelling and simulation capabilities within the Shell group, leveraging the power of the Ferrari Formula 1 team.

'Suppose some developments influence the mechanical elements of the engine, such as compression ratio, which is the primary driver in engine efficiency,' notes Poulet. 'In that case, that will lead to another journey in pressure and temperature inside the combustion chamber. Feeding these mechanical alterations into Shell's modelling software, the algorithms can generate, compare and contrast millions of possible fuel formulations that immediately identify the regions of constituents that could achieve, or exceed, the desired combustion performance targets.'

Since 2017, Shell has been heavily developing algorithms to help it identify the optimal fuel recipe for Formula 1. Shell's optimisation algorithms process over 250,000 formulations of fuel per year for the Scuderia Ferrari Formula 1 engine. It maps almost every fuel recipe that *could* be made, and then digitally tests it with the Ferrari Formula 1 engine model.

System optimisation

Along with extracting high performance from the lean burn principle, Formula 1 must consider post-combustion energy because Formula 1 engines are turbocharged. The turbocharger has a very different demand compared to the crankshaft torque requirement from the engine, as Poulet explains: 'This is a system engineering optimisation task as, if you isolate the internal combustion engine from the turbocharger, the powertrain would not be optimised for peak power performance.

‘A lack of consideration for the enthalpy of the exhaust gas post-combustion in a current Formula 1 engine will not yield the most efficient solution’

Benoit Poulet

‘An example of this would be optimising the compression ratio to generate an improvement in thermal efficiency. This is great for mechanical torque at the crankshaft, but removes enthalpy from the exhaust gas and the turbine. The enthalpy removed from the exhaust gas cannot be recovered from the hybrid part on the turbocharger, and so you reduce the scope for recovery and, therefore, deployment of the MGU units on the car.

‘Overall, a lack of consideration for the enthalpy of the exhaust gas post-combustion in a current Formula 1 engine will not yield the most efficient solution.

‘Formula 1 is not a design of experiment that has no limit. With the experience we have, we can refine the fuel, engine and mapping to improve the operation. This may see losses in enthalpy in the exhaust gas that will sacrifice some potential on the ERS side but, if that yields a higher potential in overall efficiency for race conditions, it is considered.’

As the turbocharger has acoustic and oscillating pressure effects on the exhaust flow, it is also used as an input to fuel formulations to identify recipes that may mitigate some of these adverse effects on efficiency.

‘Even with today’s technology, with the advancements in AI and compute for simulation, it would be impossible to simulate all of the pressure wave oscillations caused by the exhaust gas as it exits the combustion chamber, travels down the exhaust pipes and interacts with the turbine,’ says Poulet.

‘However, it is possible to generate a very accurate energy map and enthalpy of the exhaust gas as it enters and passes through the exhaust system. We take this type of information from a 1D simulation into a 3D space, which gives us quite a precise picture of the potential of the gas exchange through the engine, exhaust and turbocharger feedback system.’

Working alongside the Ferrari engineers to design and develop back pressure reducing exhaust designs that capitalise on the post-combustion enthalpy of the exhaust gas is another significant part of the development process and partnership between Shell and Ferrari.

Shell engineers working in a mobile laboratory testing fuel and oil samples for evaluation and development

Shell

‘Any energy released as pressure or sound out of the engine can be harvested by the turbo and the electric machine attached to it,’ notes Poulet. ‘The flow through the exhaust before the turbine is critical for the overall performance as it contributes to the only unlimited energy recovery source in the car’s ERS.’

Lubrication side

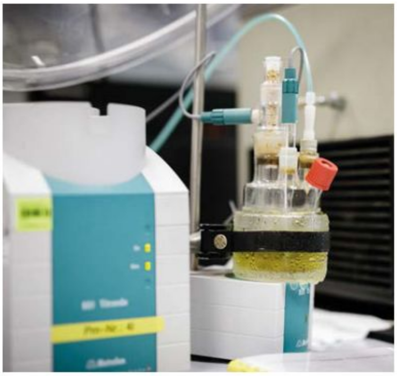
Efficient use of the energy to increase the power output in an engine would not be complete without considering lubricants.

‘We must consider the oil when we speak about the total power output over 1000bhp for a powertrain system as power dense as the current Formula 1 engines,’ says Poulet. ‘There are hundreds of kilowatts of energy released as heat, which must be extracted from the source areas of the heat and expelled to the outside air.

‘Of course, the lubrication side of the oil must prevent contact between sliding surfaces, but the heat extracting capability of the current oils is better than ever.’

So, not only must the oil in current Formula 1 engines lubricate and cool the engine components and turbo, and not generate wear, but it must also get all the calories of heat away from the engine in the most efficient way, all the while contending with temperatures as high as 1000degC without any oxidation or breakdown.

With an energy-limited system, mechanical efficiency is the biggest contributor to overall efficiency. Without friction, there would be no mechanical losses in the engine’s operation, which, of course, is impossible. The lubricant therefore separates mechanical elements of the engine with a fluid film that allows them to pass over each other without contact.



Shell

Shell F1 race fuel test formulation undergoing experiments at the lab

The FIA and Formula 1 have increased the durability and reliability requirements of the powertrain. Ten years ago, each engine only had to complete two race weekends, whereas now, every Formula 1 engine completes more than seven race weekends, or over 5500kms, more akin to the mileage covered by the race-winning car at the 24 Hours of Le Mans.

Heat control

‘A formulation of a Formula 1 lubricant that must contend with extracting a considerable amount of heat, preventing sliding contact under all race conditions, and maintaining engine wear throughout the race is very challenging to find,’ says Poulet. ‘It must be thin to achieve extreme sliding and boundary layer efficiency between the mechanical elements through the engine, but the other characteristics require very different chemistry. To tackle these challenges, Shell has developed a technology it calls GTL, a base oil technology taking natural gas and combining the natural gas atom into longer chains, making them more stable in all sorts of high-stress conditions.’

A fully sustainable fuel is the primary target for the upcoming generations of Formula 1 as it drives towards carbon neutral by the end of the decade

Unlike mPAO synthetic base oils, which can have as little as 10 per cent homogenised synthetic base oil constituents, the GTL technology developed by Shell takes the atoms of natural gas (methane) and combines them in a process that includes exerting huge pressure on the gas until it builds a liquid with the desired chain properties. In this case, the GTL process makes the resulting lubricant a 100 per cent synthetic solution, built atom by atom into chains. 'It is like being able to do the perfect recipe all the time,' says Poulet.

'The oil formulation not only needs to be the combination of low viscosity to impose a low coefficient of friction, while maintaining a buffer of oil to avoid metallic contact and have high thermal capacity and conductivity, but it must also have low volatility parameters because the FIA regulates oil consumption. Depending on the engine's characteristics, the distribution between these different parameters is not always even and often sees one characteristic more highly weighted than another.'

Traditionally, increasing power in a race engine increases the heat generated. That additional heat must be contained if engine efficiency is to improve. However, the higher the chamber temperature, the more volatile it is and the higher the risk of knock. Additionally, as Formula 1 is so aero dependent, the aerodynamicists want the powertrain package as tight as possible, including the cooling system.

'Tackling the heat is primarily the job of the engine oil,' says Poulet. 'The engine oil engineers work to develop the oil that has a higher heat capacity and a higher thermal conductivity to exchange the heat it is carrying away from the engine to the air using the smallest cooler volume possible.

'Because the quantity of energy provided to the engine is limited, more power is created through more efficient use of that limited power. This pushes the engineers to reduce the heat rejection by developing the fuel formulation to make more energy at a lower combustion temperature.'

Racing fluid test equipment at Shell's Formula 1 laboratory

Shell


Shell additive packages to improve the performance of its lubricants

Shell

Formula 1 has a mission to become carbon neutral by 2030. To do so, all suppliers and partners to the sport must take respective amounts of responsibility to achieve that target.

'Shell will continue to investigate all the elements inside the fuels to achieve this target and the extraction of their raw materials and processing stages of the fuel, not just post-combustion emissions,' highlights Poulet.

Bio-fuels

'Shell has been pushing for the inclusion of more bio sustainable components with no compromise. We were strong advocates of the passing of the Formula 1 fuel standards coming into regulation in 2022, including 10 per cent second-generation ethanol elements in the race fuel. We want to prove that this ethanol will be part of the journey of improving engine efficiency. This ethanol will be coming from non-food competing land sources, so the formulation of Formula 1 fuel will not take land away from agriculture land.'

The 10 per cent ethanol fuel percentage will facilitate several things when introduced into the Formula 1 fuels from the 2022 season onwards. The construction of the ethanol molecule means it carries a lower quantity of joules per kilogramme as a combustible vapour than the equivalent volume of Formula 1 race petrol.

However, as per all alcohol-based compounds, ethanol's evaporation characteristics mean it will extract temperature out of the combustion chamber during the initial stages of combustion. This allows the mapping engineers to lower the ignition advance, taking it closer to TDC and initiate better timed combustion. For these reasons, ethanol brings a favourable prospect to the efficiency potential of Formula 1 engines.

Design engineers can adjust several follow-on configuration parameters from these characteristics, thanks to introducing the higher ethanol content. The compression ratio is the primary beneficiary of the ethanol blend and could increase and drive the efficiency of combustion higher still.

Additionally, ethanol molecules contain oxygen. Instead of solely relying on the oxygen ingested into the engine through the intake, further oxygenation of the working fluids in the combustion chamber will occur with the higher percentage ethanol blend in the Formula 1 fuel. There is a lot of re-design and optimisation that engineers can implement into the air loop because it will no longer have the same target of kilograms per hour of oxygen from ingested air.

Shell currently has seven products inside the Ferrari Formula 1 car, including fuel, lubricant and e-fluids used to cool the power electronics, electric motors and controllers. These are designed, developed and supplied as part of the system engineering partnership the company has with the team. A fully sustainable fuel is the primary target for the upcoming generations of Formula 1 as it drives towards carbon neutral by the end of the decade.

Prepping for its first runs of the year, the updated Robinson Race Cars '69 Pro Mod Camaro in the workshop

Lessons learned

UK-based Andy Robinson Race Cars emerge from a major Pro Mod crash stronger, lighter and hopefully quicker, too

By LAWRENCE BUTCHER

Rear wing has been mounted lower than on previous incarnation of the car to reduce drag, but also giving the team more options with the Gurney flap

Hampshire, UK-based Andy Robinson, founder of eponymous Robinson Race Cars (RRC), has been an active drag racer since the early 1970s, achieving great success and winning no fewer than seven MSUK championships. His company is one of the UK's few dedicated drag race chassis builders, responsible for producing some of the quickest drag cars in Europe, while also undertaking specialist fabrication for a host of other racing disciplines.

Over the past two decades, though, his name has been synonymous with the Pro Modified class of cars, and his team is currently putting the finishing touches to its latest machine, Anger Management 2.0, a '69 Chevrolet Camaro.

For those not familiar with drag racing, Pro Mod is home to the fastest machines outside of nitro-fuelled Top Fuel Dragster and Funny Car, with the top racers running the quarter mile in the 5.6 to 7-second bracket at terminal speeds over 250mph. Since the mid-'90s, its popularity has rocketed and the class has gained pro touring status with the NHRA, while regional championships have appeared across Europe and the Middle East.

The NHRA regulatory framework, which is more or less followed by series around the world (even if they run under the FIA's remit), specifies that Pro Mods must be 'door slammers' ie full-bodied cars with two functioning doors (ruling out Funny Car-type one-piece bodies), built to SFI 25.1 safety standards, and retain the recognisable shape of the production car on which they are based.

A complex maze of engine, clutch and chassis settings with the single goal of pushing the rear tyres to the limit of available traction, but no further

Engines are limited to V8, single camshaft units with capacity and vehicle weight dictated by the form of induction – also known as the power adder – used, effectively creating a Balance of Performance system.

FIA-managed rules in Europe tend to lag slightly behind the NHRA, mainly for cost and rules stability reasons, but, as of 2020, the NHRA permitted both Roots and centrifugal 'Procharger' superchargers, turbochargers and nitrous oxide injection. Various restrictions on boost levels, transmission types and other parameters are also used to try and ensure parity between the wildly different engine combinations.

New FEA-designed engine support plate is pocket milled for weight loss

Success story

The story of this car began in 2012 when Robinson began building a new car to replace his Studebaker Commander, in which he had won three British MSA championships. The new racer would take the form of the classic Chevy Camaro and was a resounding success.

In 2014, Robinson became the first UK driver to break into the five-second bracket, running a 5.968-second pass at 239mph during the FIA European Finals at Santa Pod Raceway in England.

A recent rule change allows the front chassis section to now be fabricated from titanium tube, bolted to the chromoly frame rails

The car went through a variety of updates and secured four MSUK Pro Mod titles, but then, at the last round of the 2018 season, Robinson suffered a spectacular crash having reached the final, writing off the car.

So began work on a new version of the car, shown here, which should have made its first passes by the time this magazine hits the shelves. It still uses a '69 Camaro-style body, but builds on the lessons learned with the first iteration, and the engineering lead was taken by Andy's son, Luke, also the car's crew chief, who explained the development process to *Racecar Engineering*.

Perfect balance

It is easy to dismiss racing in a straight line for just a quarter of a mile as a straightforward process. At this level, it is anything but. Harnessing in excess of 3000bhp effectively requires a perfect balance between a multitude of factors, with racers navigating a complex maze of engine, clutch and chassis settings with the single goal of pushing the rear tyres to the limit of available traction, but no further.

For example, if engine power is ramped up too quickly on launch, or that power is transferred through the clutch too rapidly, traction will be lost. And almost certainly the race. Similarly, if the weight transfer rate on launch is not just so, or the tyre pressure out by a hair, the result is the same. Balancing these factors, with track and atmospheric conditions fluctuating from run to run, is no easy task.

The aim of builders such as the Robinsons is therefore to ensure they create a stable platform that allows their adjustments to have as consistent effect as possible to run as close to the limit every time in order to be competitive in what is always a tight field.

The layout of the Camaro is conventional by drag racing standards, featuring strut suspension up front, mounted to a tubular chromoly chassis consisting of four main rails that run front to back, supporting a four-link suspension and live axle at the rear. The devil is in the detail, though, and the Robinsons have paid great attention to these during the car's three-year gestation. Almost every element of the chassis has been subject to scrutiny, chasing either weight, stiffness or kinematic improvements.

Weight watchers

On this car, the foremost section of the chassis, which supports the fuel and oil tank, is constructed from a formed titanium tube, bolted to the main chromoly chassis rails. Until recently, it was not permitted to use titanium for this section, but a recent rule change now allows this approach, and the potential for weight saving made it an obvious update.

Old car chassis showing previous front suspension support arrangment, which was later found to be flexing fore and aft

TECH SPEC: '69 Chevy Camaro Pro Mod

Chassis make:	Robinson Race Cars (RRC)
Chassis specification:	SFI spec 25.1F
Engine type:	526ci, 90-degree V8; two valves per cylinder
Engine location / orientation:	Front, longitudinal
Block material:	Billet aluminium
Induction:	Roots-type supercharger
Transmission type:	Modular planetary manual
Number of speeds:	3
Drive:	Rear
Type of selection mechanism:	Air shift
Gearbox / differential location:	Centre / rear
Clutch type:	Driver-actuated with centrifugal lock-up
Clutch diameter:	11in
No of clutch plates:	three
Front suspension type:	MacPherson strut
Rear suspension type:	Four-link
Dampers:	Hydraulic
Springs:	Coil
Brakes:	Single piston front, four piston rear
Brake disc material:	Carbon / carbon
Wheels:	Front, 15 x 3.5in forged aluminium; rear, 16 x 16in (mandated)
Wheelbase:	112in
Regulation weight:	2650lb

The bulk of the changes have been made with safety in mind, but also with an eye on performance

Behind this, the four main chassis rails begin, two upper and two lower, running either side of the V8's crankcase through the cockpit to the rear suspension pick-up points. The front suspension wishbones mount to the lower rails, which are braced by aluminium plates spanning the chassis, which also form the engine mounts.

While re-designing these mounts, considerable weight savings were found by detailed FEA analysis. 'The previous main motor plate at the front of the engine was 1/4in thick and solid,' explains Robinson. 'We now use a thicker, 3/8in plate but pocket milled to different depths. We have calculated it's more than twice as stiff as the old one, but only 24g heavier.'

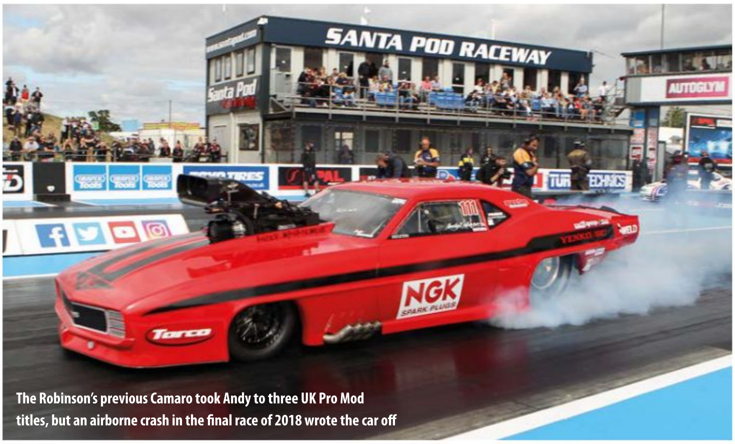
Likewise, the rear mount, already 3/8in thick, is now 225g lighter after being subject to similar analysis.

Coilover front suspension use Strange Engineering bodies and Penske internals, with double the stroke of previous iterations

Front suspension

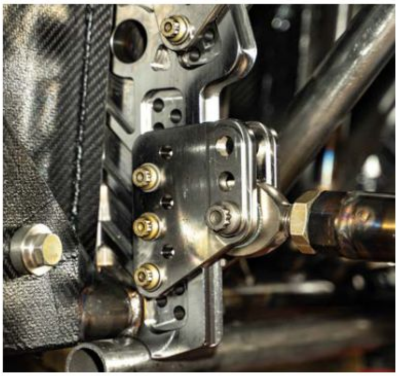
The strut front suspension also came in for revision. The previous layout, shown at the top of this page, saw the top of the struts supported by hooped sections extending out from the top and bottom chassis rails. However, as Robinson explains, 'That layout was great for engine maintenance because you could take a cylinder head off without removing the headers, but we found that the mounting holes for the motor plate were being stressed and elongating. Initially, we thought the engine was moving backwards and forwards, so we put in titanium links from the bellhousing to the chassis, but the problem persisted.'

Further analysis determined the suspension struts were flexing fore and aft,



The Robinson's previous Camaro took Andy to three UK Pro Mod titles, but an airborne crash in the final race of 2018 wrote the car off

Curved main chassis rails are a new feature, along with the seam-welded, chromoly seat pan, now permissable under new class regs



Billet RRC four-link front mounts are now an integral part of the chassis

Almost every element of the chassis has been subject to scrutiny, chasing either weight, stiffness or kinematic improvements

and the solution devised ties the top of the struts into the 'cage structure at the bottom of the windscreen pillar. This makes engine access trickier, but Robinson is confident it will cure the flexing issue with no additional weight penalty as previous bracing tubes have been eliminated.

Not only has the location of the front coilover units been revised, the dampers themselves are new. Consisting of a Strange Engineering-manufactured damper body with Penske internals, supplied by drag race suspension specialist PRS, they have approximately four inches of stroke, compared to two on the old versions.

This additional travel is not used in compression, but in droop, and, combined with a high degree of rebound damping, controls the rate at which the front wheels part contact with the track surface. If this happens at the wrong point in the early stages of a run, the weight distribution change as the car 'sees' the weight of the wheel and axle assembly can upset its balance and cause tyre shake (a violent phenomenon where the rear tyres rapidly lose and gain grip, setting up a harmonic effect that overwhelms the damping).

Further into a run, when it is necessary to have the front wheels on the ground to steer, the rebound damping is ramped down via a CO_2-actuated solenoid, controlled by a timer. A similar system is used at the rear to limit extension of the rear dampers as the car launches, due to the tyre being compressed when the initial power hits.

'Cage fighter

Moving to the centre of the car, much of the main chassis structure is dictated by the SFI safety rules, but there is scope for performance optimisation. Compared to the old car, Robinson says the bulk of the changes have been made with safety in mind, but also with an eye on performance. The most unusual feature being the asymmetric construction of the 'Funny Car' 'cage structure that father, Andy, sits within.

It was decided early on that a Racetech 4119 seat would be used. However, this full enclosure-style seat, coupled with Andy's 6ft4 stature, means space was a concern.

'It may sound silly, but we designed the chassis around the seat,' remarks Luke.

The asymmetry takes advantage of the rules to both optimise protection for Andy and facilitate maintenance. The main hoop of the 'cage was placed forward of the driver's head on the door side, a layout which allows for a reduction in the number of tubes used. On the interior side, the hoop sits level with the driver's head, easing access to the transmission tunnel. An important factor given clutch adjustments between runs are commonplace.

The main frame rails are also curved to accommodate the seat, where previously they were straight. This section of the chassis is vital to the performance of the car as it absorbs all the loads from the rear axle, transmitted through the four-link, so stiffness is the primary concern. The Robinsons previously used machined magnesium alloy 'stress plates' between the chassis rails, coupled with vertical bracing tubes, but the curved rails made this approach impractical, so regular triangulated tubes are now employed.

The final modification to accommodate Andy and his seat takes advantage of another new allowance in the SFI rules. Until recently, the floor under the seat had to feature cross bars, but it is now permissible to use a chromoly seat pan, seam welded in place, with a pair of 'scraper' bars extending below the floor. These protect the pan in case the car ends up skidding along the track on its floorpan. This update meant the seat could be mounted below the main chassis rails, reducing any need to increase the height of the roofline for head clearance, which would carry an aerodynamic penalty.

Rear suspension

Significant changes were also made at the rear of the chassis, predominantly around the four-link suspension system and its mounting. The rear suspension centres on the rear axle, consisting of a rear end housing with axle tubes, a third member, which carries the ring, pinion and driveshaft, and the rearward four-link mounting plates, which also support the rear coilover damper assemblies.

The Robinsons use a four-link of their own design, which features multiple mounting options to allow for varying bar heights and angles. The mounts are machined from solid billets and feature a keyway-based system to ensure positive and twist-free location of the bars, minimising the potential for binding. In addition to increasing the diameter of the four link-bars themselves to add stiffness, a major change compared to the old car is the means by which the front mounts attach to the chassis.

With the old Camaro, as is general practice on many tube chassis cars, the mounting plates were welded to the regulation required vertical bars that brace between the chassis rails and rear crossmember tubes. On the new car, the mounts themselves replace the vertical bars, taking advantage of a rule that allows this approach.

'You can use the four-link plates themselves, if you box them in,' explains Robinson, 'but there is a minimum width given. So what we've done is design the four-link plates so they are machined down in the area where the bolt on plates are, but step out at the back to meet the regulations.

They are then notched top and bottom to locate the crossmember. Not only does it make the car easier to build on the chassis jig, it means the four-link is tied in better to the chassis, and is lighter as well.'

Carbon spine

The Camaro is clad in bodywork constructed from a combination of carbon fibre and Kevlar, comprising front and rear sections and a pair of doors. Traditionally, the bodywork at the rear of a car like this is attached directly to the main chassis tubes via an array of smaller braces, but the Robinsons use a different approach they pioneered on the first Camaro.

Two carbon fibre spines extend back from the main 'cage structure to the rear of the car and support the bodywork, which is attached using a system of hooks and securing pins. Each spine is constructed using a combination of aluminium plate, aluminium honeycomb and carbon. The lay-up process was further refined for the new car, with Robinson conducting an FEA analysis of the aluminium core.

'On the old car, we basically just machined round holes,' he says. 'For this car, we modelled it in CAD and ran FEA, changing the shape of the weight-saving holes to find the strongest and lightest way. I did a fairly basic loading situation and went through 12 iterations, including the original design, and have ended up with a triangular hole design more like a truss.'

Through this iterative process, Robinson added material in areas identified as being more stressed and removed it where not needed, resulting in a 225g weight saving for each spine.

Though taken from the same mould as the previous body the rear of the car, which features a large, flat spoiler with an adjustable Gurney flap, was subtly re-modelled. Following the lead of research undertaken by the body's original designer, Tim Hodgins, the spoiler was lowered 1.5in, which it is hoped will net a useful drag reduction. This change means the Gurney flap may have to be run higher to maintain high-speed stability, but Robinson notes that with the old car the team was running the wing fully trimmed out when conditions were good. 'I always thought that on a really good track, we had too much downforce, so now we can play with the Gurney a bit more and have just moved the baseline.'

Proven package

The Camaro is propelled by an all-billet aluminium, Noonan/BAE 521ci V8 based around the classic Chrysler Hemi architecture and mated to a three-speed Lenco planetary-type transmission. Between them sits an EZ Motorsports clutch with steel 'floater' discs, which act as a form of traction control.

Carbon and Kevlar bodywork is attached at the rear to carbon honeycomb spines, optimised through FEA analysis

The clamping load of the clutch is dictated by a combination of springs and lever arms, which increase clamping as rpm increases. To bring the clutch in sooner, weight is added to these arms and vice versa to reduce the rate at which it locks up, while the base pressure of the clutch springs can also be tweaked to dictate the initial bite.

Combined with the engine parameters, the clutch is one of the most important tuning elements to get right for a successful pass.

The engine runs on methanol, with forced induction provided by a belt-driven Roots supercharger, built by Mike Janis Superchargers. It was one of the few parts that could be saved from the original car and its specification remains largely unchanged. The fuel and ignition systems, on the other hand, have been completely revised.

Previously, a programmable magneto ignition system was used, but this has been replaced by a coil-near-plug set up from MSD. Robinson says there are a number of benefits, including greater flexibility to alter ignition timing over a wider range throughout a run. Although the magneto spark timing could be altered on the fly, it was limited by the mechanical action of the rotor arm.

Fuel system

The fuel injection system is entirely mechanical. Fuel to the engine is supplied by a pump driven off the camshaft, meaning flow increases with engine rpm. However, the increase in mass flow to the injectors is not linear. This is for two reasons. Firstly, the pump does not deliver a linear increase in flow rate. Secondly, the fuel supply system features time-activated poppet valves that open to adjust the fuel curve as the car proceeds down the track.

The primary control of fuel flow to the injectors is via a barrel valve located at the inlet to the injector hat, controlled by the driver through the throttle pedal. As throttle is applied, the barrel valve, which contains the main fuel metering jet, opens and fuel is able to flow through to the distribution blocks that feed fuel to the injectors.

'I always thought that on a really good track, we had too much downforce, so now we can play with the Gurney a bit more and have just moved the baseline'

Luke Robinson, engineering lead and crew chief at ARRC

In its previous iteration, the engine ran no fewer than 28 injectors, with eight located in the supercharger hat, two in the supercharger body, eight in the inlet and a further eight firing directly onto the back of the inlet valves. The injector count is now lower, but the fuel delivery more refined.

Rather than having eight injectors in the blower hat, there is a spray bar system that supplies around 50 per cent of the engine's fuelling needs, with a further four in the supercharger body and eight in the inlet manifold.

The in-head injectors were removed for several reasons. The fuel they injected had minimal opportunity to atomise before it was ingested into the combustion chamber and the fuel rail sat in hot oil, raising the fuel temperature.

Currently, the Robinsons have decided to stick with this proven engine package, refined to provide greater efficiency, and hopefully consistency, too. However, Robinson says the car has been built with sufficient space in the front part of the chassis to accommodate a centrifugal supercharger and gear drive if necessary. Though these are currently not permitted in European competition, the NHRA has allowed them since 2020 and they are proving potent.

With FIA racing set to re-start in earnest this summer, as various restrictions across Europe are eased, the team hopes to have the car back in its rightful place at the sharp end of the European Pro Mod field.

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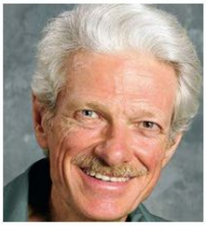


Three's a crowd?

The pros and cons of multiple trailing links with leaf spring suspensions

By MARK ORTIZ

Leaf spring slider shackles are designed to offer a more consistent spring rate and eliminate any potential bind with regular shackles. Note this system is using a monoleaf spring

Q Mark, kudos again to you! Us 'grass roots' racers owe you a great debt for the invaluable technical understanding of all types of race car suspension systems.

So here's my question, in relation to vintage leaf spring suspension.

First, on road course cars with live rear axles, the simple three link with heim joints / rods anchoring one upper and two lower arms, with a Panhard bar for lateral control, has been the most common, simple and effective solution – whether using leaf springs or coilovers.

Many of the cars with leaf springs use a 'slider' configuration – that is plates with four holes for u-bolts welded to the axle pad and one similar below the leaf spring, with tubular steel spacers sandwiched between them with the length of spacer providing a gap that allows the axle to resist bind in bump and rebound.

What are your thoughts on such suspension configurations? And can you explain what the positives and negatives are of the three link with heim joint system described?

THE CONSULTANT

A The short answer is that this is one of a variety of strategies used to 'work' the rules – specifically, rules that say:

- The car has to have the same style of springs as the stock suspension, but spring rates can be changed.
- All stock suspension members must remain in place.
- Bushings may be replaced with others of different design and material (I suppose this could be extended, perhaps just through interpretation, to allow alteration of other mountings, such as spring to axle).
- Traction aids, normally meaning longitudinal links, may be added.
- Lateral locating devices may be added.

The original 'traction aid' for leaf spring live axles was Traction Masters. These were introduced in the 1950s and consisted of a trailing link mounted right under each spring. These attached to the spring clamp and the front spring mount, making them a bolt-on item (and therefore particularly popular with the street crowd).

The idea was to control spring wrap-up, rather than achieve any fundamental alteration in geometry. The rules have since been interpreted to allow any combination of added trailing links, and / or torque arms.

The original idea with the bushing rule was to allow people to substitute urethane or metal bushings, or spherical joints, for soft rubber bushings to reduce compliance. However, people figured out that it is also possible to use foam rubber bushings on a link to functionally disable it, while leaving it in place to comply with the rules.

This is a popular trick with first generation Mazda RX-7 owners. The car comes as stock with four trailing links and a Watt linkage.

The idea was to control spring wrap-up, rather than achieve any fundamental alteration in geometry

Why remote shock reservoirs?

Q Why do people use remote reservoirs on shocks, when they could have the gas piston and the gas in the shock and save a bunch of cost and complexity?

Having a remote gas canister on your coilover frees up more space within the damper body for travel

THE CONSULTANT

A The biggest reason is to get more travel from a given length shock. If the gas reservoir is in the shock body, it takes up some of the length that could be used to add travel.

When the reservoir is remote, it can be bigger, reducing the gas spring rate. However, gas spring rates are generally small, even with integral reservoirs. Additionally, in some cases an extra valve is incorporated in the reservoir, which mainly softens high-velocity compression damping.

There is some possibility of interconnecting shocks using the same plumbing, but this is limited by the fact that only shaft displaced volume goes into the reservoirs. This means that any interconnective system must use very high pressures to generate significant forces at the wheels.

If we have three trailing links and a Panhard bar, using leaf springs actually increases complexity, compared to using coilovers

The trailing links are not equal length and parallel. The uppers are shorter than the lowers, and they converge a bit toward the front in side view. This makes the suspension bind a little in roll, especially when lowered. Racers generally leave the lower links active and fit non-compliant bushings in them, then put foam bushings in the upper links, and add either a single central upper link or a torque arm.

As for positives and negatives, three trailing links and a Panhard bar are certainly a good system, and simple. You can get as much anti-squat as you want, or as little, very easily.

I once saw a 'pump piece' article from somebody marketing a torque arm conversion that said three links don't produce as much anti-squat as torque arms, but they can if you want. It's just a matter of sloping the upper link down at the front. You can also get zero, or very modest anti-squat, with a three link, which is difficult to do with a torque arm.

Probably the only reason to use leaf springs with a three link is to comply with the rules in a specific category.

It might be appropriate here to discuss why *anybody* uses leaf springs in racing in the first place. Their main advantage is simplicity. The spring can serve as a locating system, or in some cases part of one, saving on parts. Assuming the spring has multiple leaves, it also self-damps. This was really useful before there were shock absorbers, and also in the early days of hydraulic shocks. Reason being early hydraulic shocks had very primitive valving. People hadn't yet figured out how to get adequate low-speed damping without creating excessive harshness at high velocities. Hydraulic dampers rely on viscous friction. Without valving that progressively opens as pressure increases, a hydraulic damper produces force in proportion to the square of shaft or lever velocity.

A friction damper, or the interleaf friction in a leaf spring, works on Coulomb friction. It produces the same force at any velocity, except for some amount of stiction (increased friction to initiate movement). This pairs well with a shock that has little low-speed damping.

With modern dampers, though, we generally try to eliminate Coulomb friction as much as possible.

Load points

If we have three trailing links and a Panhard bar, using leaf springs actually increases complexity, compared to using coilovers. We have more load points. We have to add sliders, and maybe even birdcages, where the springs mount to the axle. We're therefore *adding* parts to the spring system to *reduce* the number of jobs it does.

With a ladder frame, especially at the rear of a truck, it is often advantageous to have two load points, far apart, where the spring supports the frame. With a spaceframe, or something akin to one, it simplifies the structure if we can minimise the number of load points.

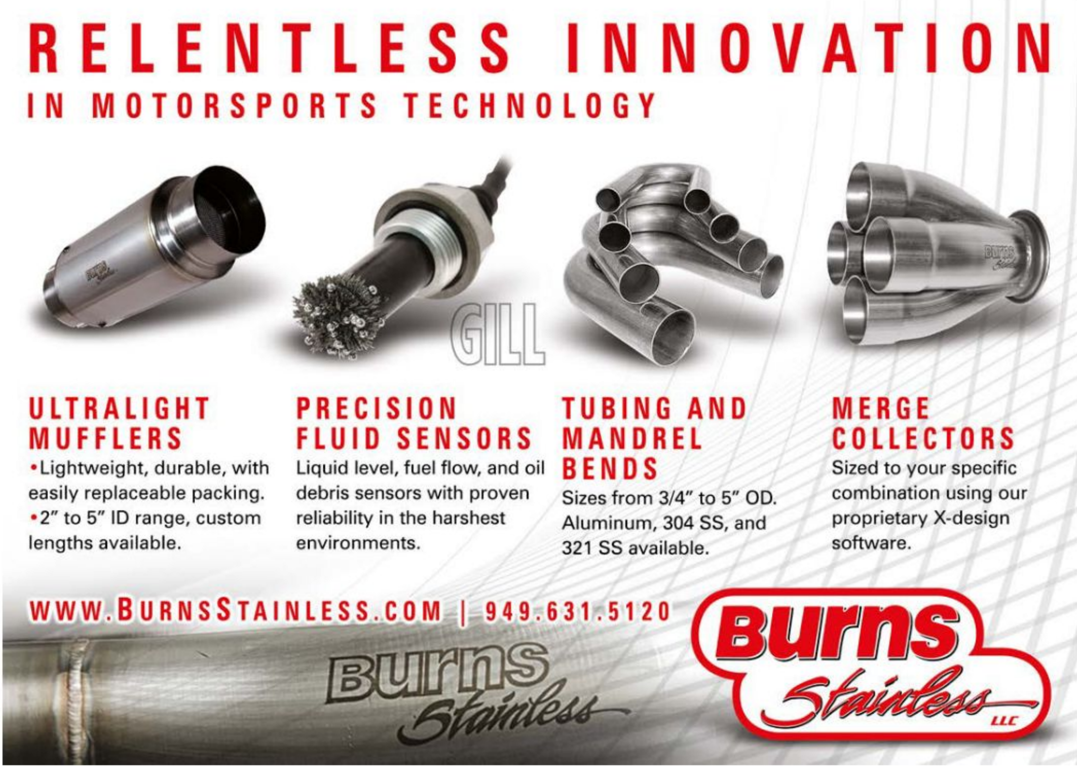
With a bit of cleverness, leaf springs can be made to provide a front or rear suspension stiffer in synchronous motion than in oppositional motion, as with the Triumph swing spring, or a camber compensator in a swing axle system. Or, it can be made to do the opposite, and function as a springing system that includes an anti-roll bar, as in C4 and C5 Corvettes and various Italian cars of the '40s and '50s. This involves mounting the spring to the sprung structure at two points, and also to the unsprung elements at two points.

One problem with leaf springs is that they tend to operate closer to their elastic limits than coils or torsion bars and, accordingly, tend to be more prone to sagging and breakage, although this depends on the specifics of the design.

CONTACT

Mark Ortiz Automotive is a chassis consultancy service primarily serving oval track and road racers. Here Mark answers your chassis set-up and handling queries. If you have a question for him, please don't hesitate to get in touch:

E: markortizauto@windstream.net
T: +1 704-933-8876
A: Mark Ortiz, 155 Wankel Drive, Kannapolis NC 28083-8200, USA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The no way transfer part 1

Righting the wrongs about load transfer

BY CLAUDE ROUELLE

Let it be clear, the suspended mass does *not* rotate around the kinematic roll centre (in 2D), or around the roll axis (in 3D). You *cannot* calculate the lateral and longitudinal load transfers without considering the tyre forces and moments, or by ignoring the jacking forces.

Many right and wrong things have been written about load transfer over the years. In this article, we will cover how load transfer is explained in many vehicle dynamics books and articles, and explain what is sometimes wrong, or incomplete, with these concepts.

First, a quick reminder. As explained in a previous article, I prefer to speak about *load* transfer instead of *weight* transfer. Some people still wrongly believe that the main cause of the change of vertical load between inside and outside tyres comes from the (negligible) lateral movement of the suspended mass c of g.

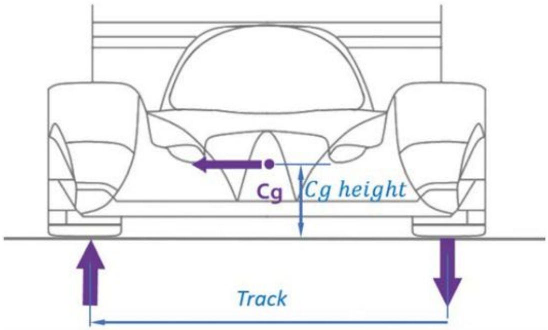
Let us start with a 2D simplified front view. The basic equation of load transfer *in steady state* in a simple 2D front view, as shown in **Figure 1**, is: Mass * V2/R * C OF G height / Track with the mass (M) in kg, the speed (V) in m/sec, the corner radius (R) and the track in m and the load transfer in Newtons.

Let us now split the load transfer (purple) in a suspended (blue) and a non-suspended (green) load transfer as shown in **Figure 2**.

Many beginners do not consider the non-suspended load transfer. On an LMP2 car, for example, each front non-suspended mass is about of 45kg, and each rear non-suspended mass about 50kg. That is around 190kg for the total of all non-suspended masses, or 19 per cent of a car of approximately 1000kg (with driver and fuel onboard). So not negligible at all.

If we do not know what the altitude of the non-suspended mass c of g is, we can consider it the wheel centre height. In most racecars, the total mass c of g is higher than the centre of the wheel. Some cars, such as those in Formula 1 with large tyre diameter and exceptionally low suspended mass c of g cars are the exception.

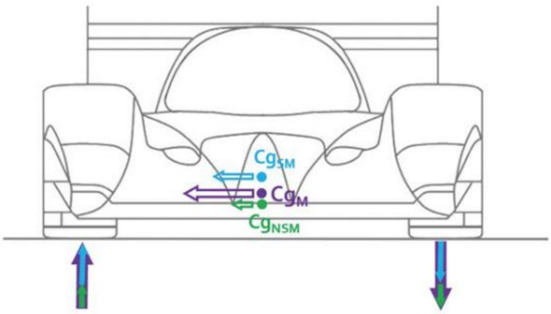
Figure 1: Simplified 2D load transfer equation



$$Lateral\ force = Mass \times lateral\ acceleration = Mass \times V^2/R$$

$$Lateral\ load\ transfer = Lateral\ force \times Cg\ height/Track$$

Figure 2: Simplified 2D suspended and non-suspended load transfers equations



$$Lateral\ SM\ Load\ Transfer = SM \times V^2/R \times SM\ CG\ height\ /Track$$

$$Lateral\ NSM\ Load\ Transfer = NSM\ v\ V^2/\ R\ x\ NSM\ CG\ height\ /\ Track$$

You cannot calculate the lateral and longitudinal load transfers without considering the tyre forces and moments

But in most cases, the suspended mass c of g (blue) is higher than the total mass c of g (purple), as shown in **Figure 2**.

The amount of the steady state load transfer is the same as that shown in **Figure 1** as the purple vertical vector that represents the total load transfer is nothing else than the sum of the green vector (non-suspended mass load transfer) and the blue vector (suspended mass load transfer). At the end, the tyre doesn't care where the change of vertical load comes from, so why do we need to split suspended and non-suspended load transfers?

The incomplete picture

1. We assimilate both left and right suspended masses (remember, we are in a simplified 2D explanation so there are only two non-suspended masses, not four) as one mass that has its c of g in the middle of the car. That would be a valid assumption for a solid rear axle suspension such as NASCAR, or the old Australian V8 Supercars, but most modern racecars have independent front and rear suspensions.
2. If we are picky, in a very tight corner (think Formula Student or a WRC rally car in a hairpin) the lateral accelerations acting on the suspended mass, the inside non-suspended mass and the outside non-suspended mass are not the same because each mass operates at different speeds, on different radiuses.
3. This is the steady state representation. It is a picture, not a movie. But once we think in a transient fashion, we must consider which of the non-suspended or suspended load transfers happens first, and by how much. In other words what is the slope of these load transfers vs time, and are these slopes constant? After all, the masses are different, as well as their I_{xx} inertias. And we must also consider how much the suspension kinematics will influence these load transfers.

Figure 3: Simplified explanation of the suspended mass load transfer, ignoring the non-suspended masses load transfers

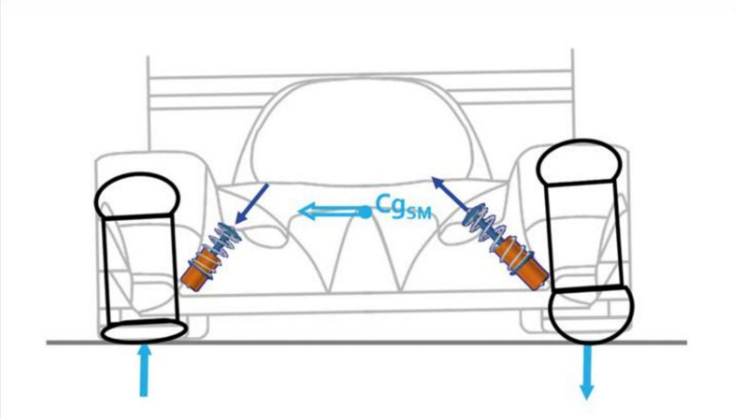
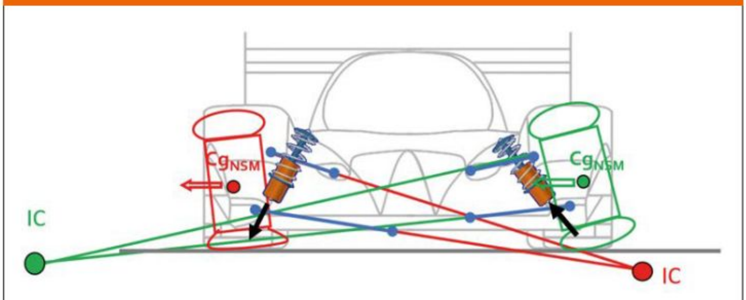


Figure 4a: Simplified explanation of the outside (red) non-suspended mass and inside (green) non-suspended mass load transfers, momentarily ignoring the suspended masses load transfer. The instant centres are here under the non-suspended mass' c of gs



Note: the vertical distance between each non-suspended mass c of g and their instant centre is usually not that big, and is exaggerated here for the sake of the demonstration

In **Figure 3**, we only look at the relative movement of the suspended mass vs the ground in a left-hand corner. The suspended mass will instantaneously rotate about a roll centre but, for now, we will ignore where that roll centre is. We will also momentarily ignore the relative movement of the two non-suspended mass vs the suspended mass and / or vs the ground.

As we can see, the right spring (outside, left of the sketch, as we look at the car from the front) will be in compression and loads, as well as compresses, the outside tyre. Meanwhile, the inside spring (inside, right on the sketch) will be in extension and unloads, as well as expands, the inside tyre.

In **Figure 4a**, we will only look at the non-suspended mass' movements vs the chassis and vs the ground with, in this case, the instant centre of both wheels *under* the non-suspended mass c of g. For the sake of visualisation, the difference of altitude between each non-suspended mass' c of g and their instant centre is exaggerated. The lateral acceleration acting on the right non-suspended mass c of g (red) will create a moment around its own instant centre that will load and compress the outside tyre, *but*, vs the suspended mass it will *extend* the right damper (black arrow).

At the same time, the lateral acceleration acting on the left non-suspended mass c of g (green) will create a moment around its own instant centre that will unload and extend the inside tyre, *but*, vs the suspended mass it will *compress* the left damper (black arrow).

Each moment is a function of the non-suspended mass, the lateral acceleration, and the difference in altitude between the non-suspended mass c of g and its instant centre.

In **Figure 4b**, we will only look at the non-suspended mass' movements vs the chassis and vs the ground with, in this case, the instant centre of both wheels *above* the non-suspended mass c of g. The lateral acceleration acting on the right non-suspended mass c of g (red) will create a moment around its own instant centre that will unload and extend the outside tyre, *but*, vs the suspended mass, will *compress* the right damper (black arrow). At the same time, the lateral acceleration acting on the left non-suspended mass c of g (green) will create a moment around its own instant centre that will load and compress the inside tyre, *but*, vs the suspended mass, will *extend* the left damper (black arrow).

Who goes there?

In simple language, we must consider 'who' does what between suspended and non-suspended load transfers, when 'they' do it and by how much.

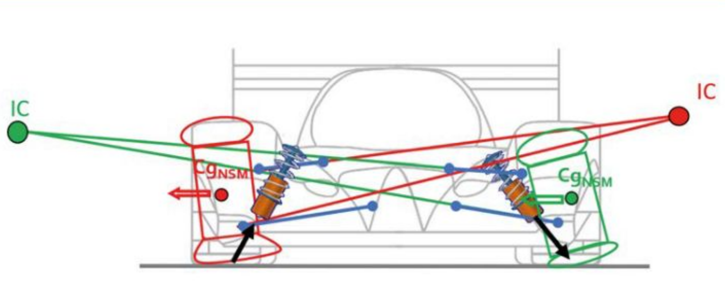
If we bring **Figures 3** and **4a** together, we see that the outside spring (left side of the sketch) is in compression because of the suspended load transfer, but in extension because of the non-suspended load transfer, while the tyre is in compression in both because of the suspended *and* non-suspended load transfers.

Meanwhile, the inside spring (right side of the sketch) is in extension because of the suspended load transfer but in compression because of the non-suspended load transfer, while the tyre is in extension because of both the suspended *and* non-suspended load transfers.

If we then bring **Figures 3** and **4b** together, we see that the outside spring (left side of the sketch) is in compression both because of the suspended load transfer *and* the non-suspended load transfer, while the tyre is in compression because of the suspended load transfer, but in extension because of the non-suspended load transfer.

Meanwhile, the inside spring (right side of the sketch) is in extension because of both the suspended and non-suspended load transfers, while the tyre is unloaded and in extension because of the suspended load transfer but loaded and compressed because of the non-suspended load transfer.

Figure 4b: Simplified explanation of the outside (red) non-suspended mass and inside (green) non-suspended mass load transfers, momentarily ignoring the suspended masses load transfer. The instant centres are here above the non-suspended mass' c of gs



Note: the vertical distance between each non-suspended mass c of g and their instant centre is exaggerated again here for the sake of the demonstration

Load evolution

Basically, we must ask ourselves how the tyres and suspension loads evolve vs time, considering the *combined* interaction of suspended and non-suspended load transfers.

Let us recap with **Figure 5**.

Basically, we have a suspended mass that sits on two non-suspended masses via the suspension springs and dampers, while each non-suspended mass sits on the ground via its tyre's spring and damper. In a simplified open loop simulation, the tyre's vertical load and deflection, and the suspension's movement will be depending on:

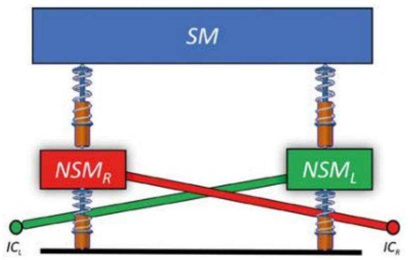
1. The amount of lateral acceleration vs time (note: in a closed loop simulation, there is no lateral acceleration unless you have tyre's grip, but we will come back to this in a future article).
2. The suspended and non-suspended masses
3. The suspended and non-suspended mass' c of g location, taking in account that because of suspension and tyre deflections, these c of gs will move both vertically and laterally.
4. Each suspended and non-suspended mass I_{xx} inertia (and I_{yy} for longitudinal accelerations)
5. The location of each non-suspended mass instant centre (IC). Again, taking into account that, because of the suspended and two non-suspended mass' movements, these instant centres will also move vertically and laterally. In other word, kinematics will make a difference. And, unfortunately, compliance, too. I say unfortunately because while compliance can be limited with good design, it cannot be eliminated.
6. The suspension springs' (especially pre-load) and dampers' characteristics, as well as tyre vertical stiffens and damping. Most of these inputs are rarely linear. That could make the simulation complicated.

Simple first, then complicated, not the other way around

In part two, we will compile a system of three differential equations of the second order, and then go through the maths and numerical illustrations. But bear in mind we have not yet spoken about suspended geometric and elastic load transfers, or the influence of the tyres' lateral forces on jacking forces and subsequent ride height variation. Or the difference between kinematics and force-based roll (and pitch) centres. Or the infamous tyre overturning moment, M_x. And we are still on 2D (two wheel).

But simple first, *then* complicated, not the other way around.

Figure 5: Simplified 2D presentation of inputs for suspended and non-suspended loads transfers



To this we have to add the lateral acceleration as a single value in steady state or, for transient simulation, a function that is time dependent

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

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CONTACT
Claude Rouelle
Phone: + 1 303 752 1562
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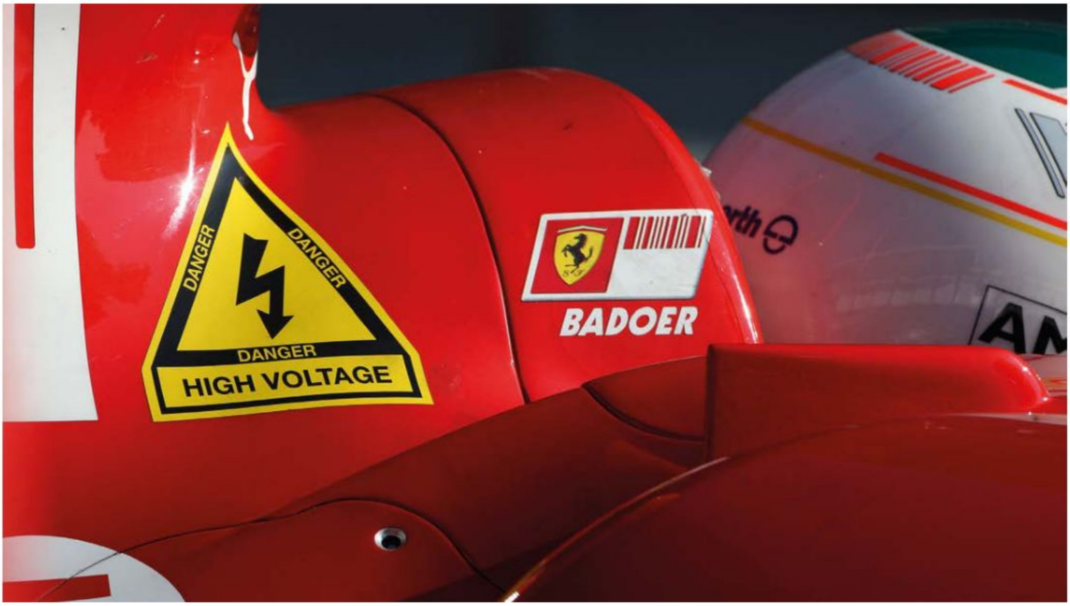
System addicts

How the role of the race engineer is changing with the ongoing march of electrification

By JAHEE CAMPBELL-BRENNAN



Photos: XPB

Formula 1 opened the door for hybrid powertrains over a decade ago in 2009. Back then, the technology was known as a Kinetic Energy Recovery System (KERS)

To stay relevant and command the large investments needed to keep itself at the cutting edge of technology, motorsport has to stay somewhat relevant to the mainstream, road car-based automotive industry.

More and more, electric powertrains are being incorporated into high-level racing. Formula 1 was ahead of the curve in 2009 with its hybrid Kinetic Energy Recovery System (KERS), while in 2012 Audi led the way in the Sportscar world with the R18 e-tron Quattro LMP1 platform with its diesel-electric hybrid powertrain.

More recently, Formula E launched in 2014 as the first full-electric race series backed by the FIA and, with the recent announcement of the Electric GT series planned for 2023, seemingly the industry is not looking back.

In hybrid systems, the working concept is clear – incorporate an electrical element to the powertrain to augment the output of the internal combustion engine (ICE). The intent is not just to 'add on' power to the IC engine in the same way as something like turbocharging, it's intended to increase the efficiency of the vehicle, capturing kinetic energy that would otherwise be wasted as heat through the friction braking system and using that to drive electric motors. The result is a decrease in fuel consumption over the duration of a race.

Close competition

With hybrid prototypes competing against non-hybrids in the World Endurance Championship and Le Mans, regulations generally stipulate a similar maximum energy output across the grid to ensure the championship remains competitive. Logically, hybrids have downsized engine capacity relative to non-hybrids due to this.

From a performance point of view, the penalty incurred through the additional weight of the system is offset by traction advantages and reduced fuel consumption over a stint, meaning fewer fuelling stops. There is certainly an inherent performance advantage to using the technology, so in practice Equivalence of Technology (EoT) balancing is used to keep non-hybrids and hybrids competitive.

Hybrid boosting is achieved with different configurations, but, so far, motorsport has always been a parallel arrangement in which the electric motor, ICE or both have the capacity to supply torque to the wheels at any moment.

In LMP1 platforms such as the R18, the electrical system supplied and harvested energy from the front wheels only. Combined with the ICE, this created a 4WD system, which had obvious benefits to traction at corner exit. In contrast, the Toyota TS050 LMP1 platform supplied both the front and rear axles with electrical power.

In the open-wheel racing formats of Formula 1 and Formula E, the electric motor acts on the rear wheels only.

In harvesting kinetic energy to store as electricity, the electric motors switch operation to serve as generators by inducing a negative torque at the wheels. This process is known as regenerative (regen') braking. Energy is sent back to the energy electrical energy storage system for later deployment.

Managing the powertrain's function in hybrid racecars requires really quite a

In the WEC, where hybrids compete against non-hybrids, Equivalence of Technology (EoT) was used to level the playing field and ensure close racing

Various approaches have been taken to hybrid powertrains. The Audi R18 used the front axle to deploy and harvest kinetic energy

different approach to the way the cars are both operated from an engineering point of view, and how they are driven.

In LMP1 and Formula 1 hybrids, the energy recovery system's deployment is linked to the powertrain control strategy, which is a driver-switchable function. Hybrid deployment and harvesting is blended seamlessly with the throttle and braking system and offers a wide range of options in both the intensity and duration of acceleration and regen' through steering wheel switches.

Managing the powertrain's function in hybrid racecars requires really quite a different approach to the way the cars are operated from an engineering point of view

'In the early days, even before the car left the pits, we would have to set aside a five-minute window simply to go through the switch set up sheet, which would be used to configure all the switches and systems,' explains Howden Haynes, race engineer and technical director on the Audi R18 e-tron Quattro programme. 'This did fade out as the cars became more intelligent, but in year one it was a huge change in philosophy.

'Drivers were making multiple changes to the hybrid system throughout every lap of a 24-hour race, and there was a massive amount of communication between the driver and race engineer to tell them what powertrain mode to be in, what strategy to be using, things like that. Roles switched from just being a driver to being more like a systems administrator.'

Power deployment

Rules stated that a set amount of energy could be recovered and deployed per lap (2MJ for the initial years), so the focus was on understanding where best to use that energy at each acceleration phase.

This ultimately was a variable calculated with simulation to arrive at a strategy that produced the quickest lap time, and therefore the most efficient use of the hybrid system.

'Ultimately, it was another tool in your strategy box. There was a lot to learn and explore but, if you didn't get it all right, you were way off the pace,' adds Haynes.

In full-electric Formula E, where maximising regenerative power is crucial to even finishing the race, let alone winning, cars leave the grid with only around 70 per cent of what's needed to reach the finish line. The remaining 30 per cent must be gathered through regenerative braking.

This transforms the race into a game of energy management rather than outright speed and, with an overall energy consumption limit for the race, a successful strategy becomes like a long distance running event in which pace must be managed in order to not burn out towards the final stages.

'You can over consume energy at the start of the race to make passes and push forwards but, in doing this, you will then have to rein it in towards the end of the race to avoid running out of energy,' explains Jamie Gomeche, race engineer for Formula E at Dragon / Penske Autosport.

'Alternatively you could under consume at the start to save energy and make an attack later in the race.

'This is where strategy wins or loses a race. The biggest factor in this is really where you are at the start. If you're at the back you might gamble more and attack or, if you're at the front, you would play it a little safe and just do what you need to stay where you are.'

Management technique

Kinetic energy is harvested any time the throttle is closed, so in certain situations driving techniques need to be coached to minimise the time the driver spends on throttle – 'lift and coast' being the main one.

'The lift and coast technique was something that came into its own with hybrids as a method of fuel saving, and to provide the duration of regen' we needed to get the charge required into the system,' explains Haynes.

Contrary to conventional race engineering, in which average throttle percentage is a metric used to understand how effective a driver is being over a lap, this was a new idea for the team to get their heads around.

'Explaining to your driver why their team mate was quicker, even though they spent less time on throttle, made for some interesting conversations. It was all about doing more effective regen', and therefore having more power to deploy out of corners. It was a switch in thinking all around,' continues Haynes.

Maximising the regenerative power of the racecar by guiding your driver is crucial to an effective strategy then, but one of the critical considerations for battery-based electric powertrains is management of the heat produced as current is drawn from, or delivered to, the battery.

There is a very simple relationship in electrical systems linking the power flow through the circuitry and the resistance generated within the circuit. Resistance is inherent to all electrically conductive materials and is proportional to the flow of power through the system. More power means more resistance and, ultimately, this resistance dissipates a quantity of energy as heat. It is a source of loss.

To put it into perspective, there is almost a 1:1 relationship between the power output a motor can produce and the energy it can harvest. A 250kW Formula E motor, for example, will also generate around 250kW in regenerative braking, which means that between deploying or harvesting power, a significant amount of energy is being dissipated within the battery.

Thermal runaway

Batteries are particularly sensitive to running temperature and need to be kept within a specific range for both safety and performance reasons. Operating above their temperature limit can lead to a phenomenon known as thermal runaway, in which certain materials within the battery begin to break down and eventually lead to short circuit. The development of the modern BMS (Battery Management System) prevents things from escalating to that level, so it's very rare to see a battery enter the state of thermal runaway, but the management of temperature remains a key factor in design and operation.

In practice, the amount of energy the motors are flowing into and out of the battery needs to be managed by software to limit heat generation.

If the system falls outside of a specified temperature range, as a self-protective mechanism the control software will 'de-rate' the powertrain to reduce the current flow, reducing power input / output until the temperatures fall back into an acceptable area. With reduced power in deployment and harvesting capacity, a de-rated powertrain can cost races, as Mercedes F1 found early this season.

As a race engineer, it's your role to monitor and feed back the condition of the electrical systems and employ strategies to manage temperatures if necessary.

The goal all teams have is to save or regen' as much energy as possible, but the motor can only regen' so much energy before it is power limited. In Formula E, this limit is enforced by the championship, so the goal is to make sure the car is power limited as much as possible to maximise regen' energy. This means the driver and team have done the best job they can in using regenerative braking as hard and aggressively as possible.

The Hypercar regulations have replaced EoT, but energy per stint remains critical, from petrol or in combination with hybrid

'If you're not power limited, it means there is some potential regen' left on the table, usually because the grip level is low, or the corner / track surface doesn't allow it,' adds Gomeche.

Being 'power limited' means the car is operating at the top end of its range in terms of battery temperature or, in the case of Formula E, at the limit of the regulations. The software plays a large role in maximising the power available in regen', but the driver also plays an active role in maintaining this state through driving practices. Car balance, line choice and driver input all play a part in maximising the time spent power limited. Temperature management can also be influenced by the driver by avoiding running in the turbulent wake of the car you're chasing down for too long.

Common sense practices for thermal management are not dissimilar to non-electric powertrains - taking periods out in free air, using a little less regenerative braking or reducing torque output from the motor via driving technique or modulating the powertrain control strategies.

Ultimately, the propensity of a system to become power limited is a key performance differentiator, and where a particular team's application of the science becomes crucial.

Normally, the limit of regenerative harvesting is found just at the point at which the active axle starts to lose traction under braking and the car is beginning to lose stability. This is no different to traditional braking systems, of course, but does become technically interesting when you consider the axle is slowing the car down using a combination of friction braking and regenerative braking.

As a race engineer, it's your role to monitor and feed back the condition of the electrical systems and employ strategies to manage temperatures if necessary

'Traditionally, working on brake bias is about playing with front and rear line pressures but, as we have BBW [Brake-by-Wire] in Formula E, the car's software can manage the brake pressure and so is able to vary completely throughout the braking phase,' explains Gomeche.

'You can have a massive percentage variation through the braking zone, so when you calculate your anti-geometries, which brake bias percentage should you target? It means you will have multiple anti-values in every braking zone, which is something you can only get in FE or F1 thanks to the technology involved.

'Essentially, every day is a school day, which keeps things challenging.'

Seamless modulation

BBW systems hydraulically decouple the axle with regenerative braking from the brake pedal. What this enables in practice is for the friction braking effort to be electronically and seamlessly modulated in response to the varying regenerative braking capacity.

'The basic principle is that the driver presses the brake and expects a certain amount of braking torque. Regen' capacity is obviously variable due to battery SoC [state of charge] and grip, so there is a need for a system that controls frictional braking torque independently of the

brake pedal pressure,' explains Simon Zollitsch, motorsports project manager at LSP Innovative Automotive Systems.

The ultimate target is to give the driver a consistent and reliable braking torque at the wheels. When the pedal is pressed, the driver expects the same level of deceleration every time. If there isn't confidence in this, lap times suffer.

'In the first season of Formula E, this wasn't controlled very well as there was no BBW system. The cars ended up with deceleration that was different for each corner, which was very tricky for the drivers as braking points could change from lap to lap,' notes Zollitsch. 'With the BBW systems today, we also have the advantage of varying brake bias with vehicle speed, which allows braking torque to be mapped according to the decreasing aerodynamic loads on the car as the car slows down.'

Driver aids aren't allowed in most motorsport categories, so there is no ABS or TC but, with all the additional technology offering further scope to push technical regulations and stretch performance envelopes, an exceptional amount of data is monitored in order to ensure cars are operating within the regulations.

'Torque vectoring was not allowed for us, and there was also a minimum speed limit for deployment, so we were quite limited in terms of what we could do with the 4WD system to gain an advantage where others were traction limited,' adds Haynes.

To police racing, governing bodies specify a suite of mandatory sensors to keep tabs on what teams are doing with their equipment, but also to place restrictions on the level of instrumentation teams can install on their car.

In Formula E, wheel speed sensors on the driven wheels are permitted, but have a delay in output. This means they can be used for post-processing data, but cannot be used on car control systems in real time.

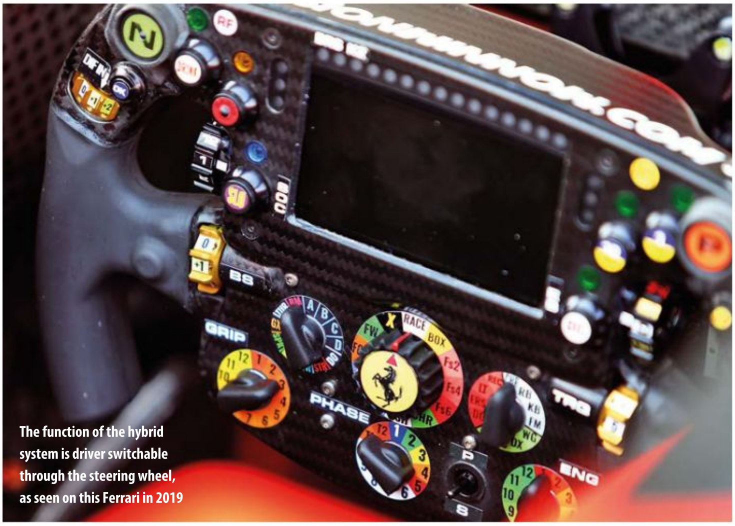
'With the lack of real-time wheel speed sensor data, the control systems of the car can become very limited, so it's all about using the little information you get to the best you can,' notes Gomeche.

Fundamentally, the mechanical architecture of the racecar remains the same, which means from a race engineering point of view, the vehicle dynamic and aerodynamic set-up considerations are very similar.

Shifting focus

Set-up for a race weekend is then an exercise in managing lateral load transfer numbers, tyre temperatures and so on, with reference to data and simulations, and the race engineer then makes fine adjustments based on driver feedback.

Qualifying set-ups must be developed for outright pace, and race set-ups



The function of the hybrid system is driver switchable through the steering wheel, as seen on this Ferrari in 2019

calculated to factor in tyre degradation with respect to the influence it has on chassis balance. But with the addition of electrical power, the focus shifts dramatically.

'We had previously spent decades understanding and perfecting things like springs, ride height, suspension geometries and so on. Normal set-up adjustments would be 0.5mm of ride height or one click of a damper, for example, but hybrid powertrains completely changed everything about what became important in finding set-up for a car,' notes Haynes.

Tuning the hybrid system to operate most effectively quickly became the most pivotal factor in performance as the infinitesimal improvements given through vehicle dynamics and aero optimisation were overshadowed by dialled in hybrid strategies.

'Springs and anti-roll bars would give you tenths of a second, but we quickly found that whether the hybrid system was set up well or not would give improvements in the order of full seconds. That was probably the biggest set-up challenge when we first started using them,' comments Haynes. 'We had to adjust our simulation methods to accommodate the new configuration.'

In series such as the World Endurance Championship and F1, where track layouts, surfaces and tyre compounds are reliable year after year, sophisticated numerical models of car, track and tyres are used to develop the car with Driver-in-Loop (DiL) simulation work. Unique to Formula E, however, is that the events are city circuit-based, which throws a spanner in the works.

Each circuit can have different layouts, surface materials and topology, which can change on each visit as repairs and adjustments are made to the road surface, so set-up decisions have a decidedly more human element.

DiL simulation work must therefore shift from track data correlation to simple driver preparation, going through procedures in great detail and just getting comfortably into the rhythm of driving the car before a race weekend.

Driver feedback

With less reliance on data, finding the window becomes more driver focussed, making them as comfortable with the behaviour of the car as possible so they feel confident to push to the limit consistently.

With so much technology in hybrid and electric powertrains, driver feedback then becomes an exercise in interpretation for the race engineer.

We're now way past the realms in which drivers are able to logically relate what they're experiencing at the wheel of the car back to the engineer in the pits. They likely

'Springs and anti-roll bars would give you tenths of a second, but we quickly found that whether the hybrid system was set up well or not would give improvements in the order of full seconds'

Howden Haynes, race engineer and technical director on the Audi R18 e-tron programme

Formula E is all about energy consumption control, which is hard enough to manage on its own, but the championship also includes an Attack Mode in which cars receive extra energy to either attack, defend or conserve to reach the flag

Race engineers with exposure to electrical systems and powertrains are only going to be in growing demand

don't have the technical understanding to comprehend the physics behind why they're feeling what they're feeling.

'The information you get from the driver is still so important. You hear about the balance and feedback you would recognise in any formula car. But in FE, with the added control systems, there needs to be so much more detail in your feedback. If issues arise with stability in braking zones with standard ICE cars, there are only so many routes you can take to rectify this – simple set-up items such as advising drivers to brake less aggressively, or change the bias.

'With the control systems in FE, you have so much control over the decelerative performance of the car,' says Gomeche. 'Driver feedback needs to become very detailed, and what was originally a simple question now has many extra parts to it. What is the feeling under your seat? Are you lacking braking performance at this phase or that phase? Is it locking or braking grip at this angle? It's a whole new level of feedback you need to relate back due to the technology involved.'

Fan interaction

Electric powertrains also unlock freedoms to do things with the powertrain you can't with the traditional ICE in the interest of making the sport more exciting for spectators and enabling interaction.

Specific to Formula E, where there are no pit stops, organisers have implemented things like 'Fan Boost', in which the fans vote for their favourite driver to have a few seconds of additional power to help with an overtake, or to defend from one. There is also 'Attack Mode', which is somewhat analogous to a pit stop.

To use Attack Mode, Drivers must go through an 'activation zone', which loses them time, but to offset this they get a period in which power is boosted by 35kW to 235kW. This brings in other forms of strategy, such as where to use the extra power, and how to manage your tyres through the power increase.

Under the race engineer's guidance, the driver then has to decide when to use the Attack Mode and what objective to set.

'As this is such an energy-focussed championship, you might not want to use Attack Mode to full effect,' says Gomoeche. 'Perhaps you want to use as little energy as possible and just aim to get back the time lost taking the Attack Mode and be neutral again at the end of the boost period. Other times you might want to exploit it to the fullest.'

With all this additional technology, the design of the racecar also has to include adequate safety measures in the event of component failure, so much effort is put into covering every possible eventuality. Perhaps the most safety-critical area is in braking. In the majority of platforms using regenerative braking, one axle will be doing the larger share of energy harvesting so, in the event of a failure, brake balance can shift significantly. If that's the front axle, as for the Audi R18, this will generate a huge amount of instability in the chassis as the bias jumps rearward.

'If a situation occurred where the hybrid system failed, you'd see a massive swing in brake bias, in the order of tens of percentages towards the rear axle, which would of course be in a braking zone. Mitigating this gave rise to intelligent braking systems, which could make instant corrections to the hydraulic bias and keep things safe,' adds Haynes.

Together with the data engineers, the race engineer is usually the first point of contact with respect to more general component failures, and will spot and manage issues as they arise. But with all the electronic control systems, failure of an individual component associated with the electrical system is not always easy to detect.

An electric motor is simpler than an ICE, and requires fewer sensors and management, but as electric cars develop, the level of complexity of electrical and control systems develops, too. Some of the technical issues present during a race may now be out of the race engineer's remit, requiring the expertise of software and system engineers to solve.

Simple things

'In essence, the Formula E car driveline is much more simplistic in its architecture than a traditional powertrain. With less moving parts and impressive levels of efficiency, you can see its appeal. And with high levels of reliability across the car, battery or powertrain issues are becoming an old school way of thinking,' finishes Gomeche. 'However, there are different parameters that require monitoring when compared with IC powertrains, so the role of control and system engineers are forever evolving. But, as the championship, and the electric car as a whole, continues to make strides, the perception of what is possible needs to be questioned every day.'

Hybrid and electric powertrains certainly shook racing up, and added additional layers of complexity to the execution of a good race, but, if there was any occupation where a challenge is welcomed, it's race engineering.

It wasn't long before the new systems were understood and exploited to edge the competition, which is as now fierce as ever, even if the auditory experience isn't.

With the popularity and external motivation to keep moving towards further electrification within racing powertrains, race engineers with exposure to electrical systems and powertrains are only going to be in growing demand for the advancements that are undoubtedly coming in the future of the sport.

Liquid assets

In the first of a new series aimed at better understanding the changing roles of those employed within the racing industry,* Racecar *looks at the part 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.'

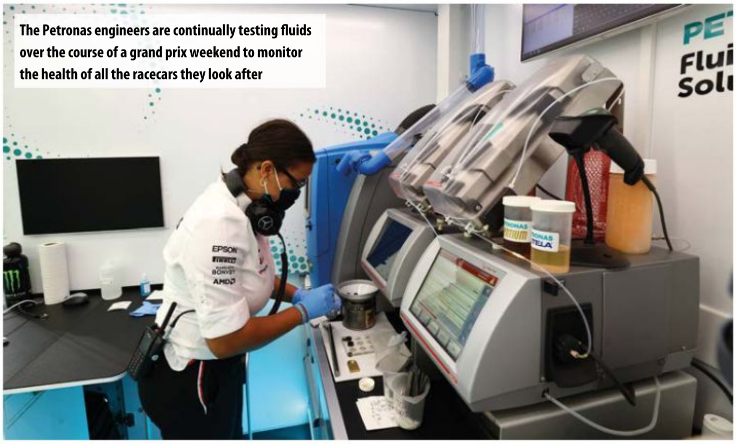
For meaningful lubricant analysis, some baseline samples also need to be taken.

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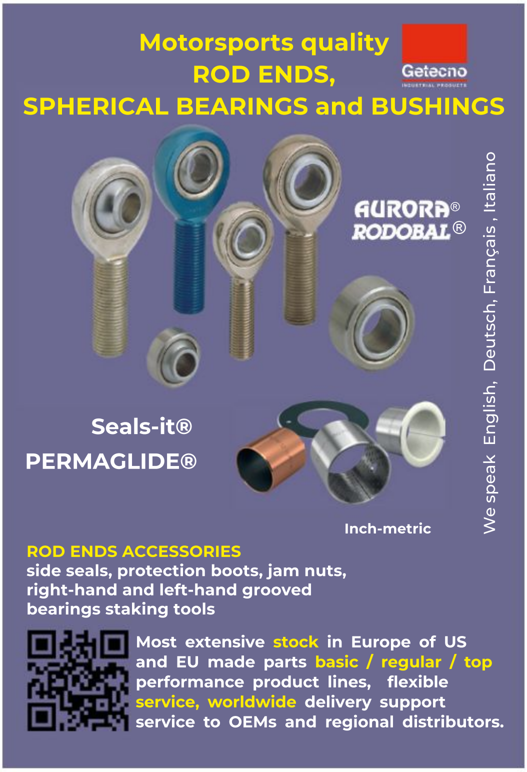
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and we have the right processes and tools in our arsenal, so we can do our job in the knowledge that the other person is doing their job at the same level.

'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 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.

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.'

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

En De Liow

Petronas supplies no fewer than eight cars on the Formula 1 grid, including McLaren, Aston Martin and Williams, meaning the two Petronas engineers have busy race weekends


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Of beams and pogo sticks

The fundamentals of vehicle dynamics – part one

By DANNY NOWLAN

One of the things that astounds me on a daily basis is, apart from a few exceptions, how many people's conceptions of vehicle dynamics have never evolved past the horse and buggy era. Where this is symptomatic is when you, say, challenge the concept of lateral location of the roll centre, or suggest a particular value of bump steer is not correct. What inevitably flows is a spirited defence that has very little basis in fact and quickly turns into a dumpster fire.

The thing that really drives this is not just a lack of awareness of the numbers, but a failure to understand what *drives* these numbers in the first place.

The purpose of this next series of articles is to try and cut through the nonsense and get to the fundamental processes that make the dynamics of a racecar tick. This way you will be armed with the knowledge needed to navigate your way through the jungle.

In this first article of the series, we'll be discussing what drives tyre loads. Stability and performance are all very sexy but, if you don't know what drives the tyre loads, you might as well not even bother turning up. Once we understand that, the performance stuff comes out in the wash, and we'll return to discuss that in part two.

Everything you need to work out tyre loads, and all the factors that drive suspension geometry, come from this basic understanding

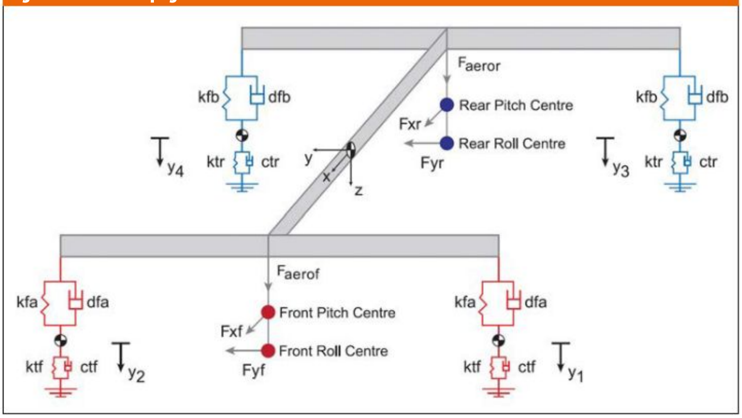
Fundamental core

The beating heart of any racecar is the beam pogo stick visualisation. Whether you are dealing with a road car or a fire breathing LMP1 / Formula 1 car, that shown in **Figure 1** is its fundamental core.

To keep things simple, I've omitted anti-roll bars, third and heave springs, jacking forces and aero side forces and drag force at the c of g. The only things needed to make this complete are the applied tyre forces at the roll and pitch centres and the D'Alembert forces at the c of g. But, honestly, at this point we are nit picking.

The important thing is that everything to work out your tyre loads, body and pitch angle and wheel movement that drives your suspension geometry come from here. Understand this and it will all fall into place.

Figure 1: The beam pogo stick visualisation of the racecar



The first spin of this is solving for the lateral equilibrium case to solve for the magic number, or the lateral load transfer distribution at the front. The way you do this is by solving for the roll angle, and then the tyre loads pop out in the wash. The way to do this is outlined in **equations 1-7**. Here, the symbols are as follows:

EQUATIONS 1-7

$$rcm = rcf + wdr*(rcr - rcf) \quad (1)$$
$$tm = wdf*tf + (1-wdf)*tr \quad (2)$$
$$hsm = h - rcm \quad (3)$$
$$rsf = (krbf + kfa)*ktf/(kfa + krbf + ktf) \quad (4)$$
$$rsr = (kfb + krbr)*ktr/(kfb + krbr + ktr) \quad (5)$$
$$prm = tf^2*rsf/(tf^2*rsr + tr^2*rsf) \quad (6)$$
$$prr = (tr/tm)*(wdf*rcf + prm*hsm)/h \quad (7)$$

The beating heart of any racecar is the beam pogo stick visualisation

rcm = mean roll centre (m)
rcf = front roll centre height (m)
rcr = rear roll centre height (m)
wdr = weight distribution at the rear of the car
wdf = weight distribution at the front of the car
h = c of g height of the car (m)
rsf = wheel spring rate in roll for the front (N/m)
rsr = wheel spring rate in roll for the rear (N/m)
prm = lateral load transfer of the sprung mass due to forces applied at the mean roll
$centre$ = (this is determined by the springs and bars)
prr = total lateral load transfer distribution at the front (this includes the effects of the roll centres and the springs and bars)
tm = mean track of the vehicle

The reason we bother with all this is so we can get a simple static approximation of the tyre loads for a given front and rear lateral force, as shown in **equations 8-11**.

Here, the symbols are:

EQUATIONS 8-11

$$L_1 = (wdf{*}mt{*}g + Faero\_f)/2 + prr{*}(Fyf + Fyr{*})h/tm \quad (8)$$
$$L_2 = (wdf{*}mt{*}g + Faero\_f)/2 - prr{*}(Fyf + Fyr{*})h/tm \quad (9)$$
$$L_3 = (wdr{*}mt{*}g + Faero\_r)/2 + (1 - prr){*}(Fyf + Fyr{*})h/tm \quad (10)$$
$$L_4 = (wdr{*}mt{*}g + Faero\_r)/2 - (1 - prr){*}(Fyf + Fyr{*})h/tm \quad (11)$$

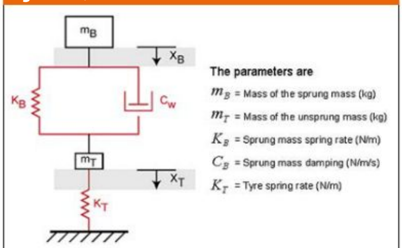
L_1 = front left tyre load
L_2 = front right tyre load
L_3 = rear left tyre load
L_2 = rear right tyre load
mt = total mass of the vehicle
$Faero\_f$ = front aero load
$Faero\_r$ = rear aero load
Fyf = lateral force applied to the front axle
Fyr = lateral force applied to the rear axle

What we have presented in **equations 8-11** isn't the whole story, but it's a great rule of thumb to put some numbers to what is going on. We'll discuss this more in part two.

For now though, an even more fundamental basis of the beam pogo stick model is the quarter car model approximation. To refresh everyone's memory, it is shown again in **Figure 2**.

Effectively, the beam pogo stick is four quarter car models held together by a bunch of beams. Understand this and everything will make a lot more sense.

Figure 2: Quarter car model



Effectively, the beam pogo stick is four quarter car models held together by a bunch of beams

The reason we are discussing the quarter car model again here is to speak about one of its least understood, yet profound impacts. That is the relationship between the movement of the damper and the unsprung mass, and the equivalent spring rate. This is unquestionably the biggest blind spot in vehicle dynamics analysis, but it can be summarised by **equation 12**.

$$K_{eq} = \frac{K_B \cdot K_T}{K_B + K_T}$$
$$\%x_B = 100 \cdot \frac{K_T}{K_B + K_T} \quad (12)$$

Where,
K_{eq} = the combined spring rate of the tyre and main spring
K_B = body or spring rate at the damper
K_T = tyre spring rate
$\%_{xb}$ = percentage movement of the body spring to total displacement of the combined quarter car

The most common way I see this blind spot manifested is when people see a damper trace and equate it either to movement of the tyre or that of the chassis in its entirety. Both are fundamentally flawed. To understand why, this let's consider the two following examples.

The first is from my previous article about the effects of bump steer on a V8 Supercar. To refresh everyone's memory, the bump steer curve is shown again in **Figure 3**.

In that article I said that shown in **Figure 3** was a mild case, though some people have since said it was an extreme case. If this was a road car, and you have to design for kerb strikes of +/- 100mm, that would be a fair point, but does that argument stand up for racing purposes? In particular, our V8 Supercar example? To review this, let's consider some ballpark supercar numbers, as presented in **Table 1**.

Table 1: Typical spring numbers for a V8 Supercar

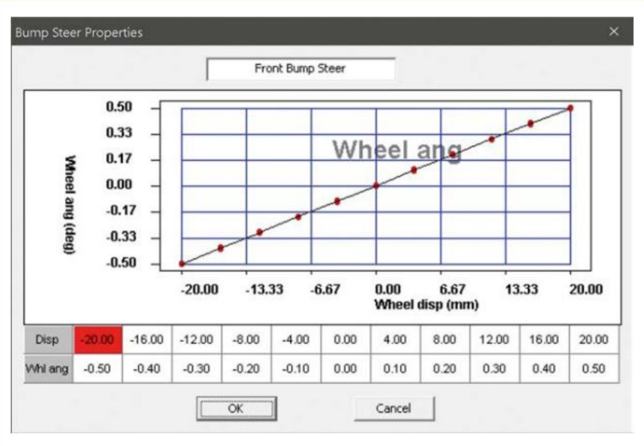
Item	Spring rate
Body spring rate at the wheel	50N/mm
Tyre spring rate	300N/mm

Using **equation 12**, let's now put some rubber on the road. This is shown below.

$$K_{eq} = \frac{K_B \cdot K_T}{K_B + K_T} = \frac{50 \cdot 300}{50 + 300} = 42.9N/mm$$
$$\%x_B = 100 \cdot \frac{K_T}{K_B + K_T} = 100 \cdot \frac{300}{50 + 300} = 85.7\%$$

This means the effective spring rate of the supercar tyre is 42.9N/mm. There is nothing particularly earth shattering there. Since the wheel rate is so soft, this is to be expected.

Figure 3: Front bump steer curve



The first key to understanding vehicle dynamics is to understand your tyre loads and what drives them

However, where things get really interesting is with the second number. The percentage of damper movement compared to total movement is 85.7 per cent. This means that if you are seeing a damper / wheel movement of 40mm, the tyre movement is in the order of 6-10mm in terms of the unsprung mass movement.

Given that bump steer acts on the movement of the unsprung mass, looking at **Figure 3** we were lucky to see maybe 0.2-0.3 degrees of bump steer at the tyre. This is why I said it was a mild case.

Road vs race

This also shows a key difference between how you approach chassis engineering for a road and a racecar. Since the circuit environment is so much more controlled, in a tarmac racing case we can manipulate the bump steer we want. Toe steer at the rear in the British Touring Car Championship in the mid-'90s is a classic case in point.

But for rally and road car use, it becomes a different ball game entirely since now you have to take into account the kerb and extreme road surface deflection.

This also illustrates another example with assessing bump steer that can sometimes be missed in a conventional test. Typically, a favourite road car metric is to rotate the chassis on a rig to see the bump steer and roll centre variation. That has its place but, as we can see in this example, it's a bit of a misleading test because what is contributing to the roll is the motion of the sprung mass. As our worked example shows, what is driving the roll movement here is chassis movement. If your test isn't duplicating that, you are not in the hunt.

The other thing this neatly illustrates is, arguably, the biggest suck you in vehicle dynamics analysis. When people look at a damper trace, they generally equate it to bump movement. Remember though, what you are seeing is an output and not an input, and that can be readily verified by looking at both the beam pogo stick and the quarter car model. You can also see the in-depth equations explaining this in my book, *The Dynamics of the Racecar*.

Roll angle calculation

To wrap up this discussion, let's look at the derivation of how to calculate roll angle for a racecar. This is a great example of combining the beam pogo stick and quarter car models. The following sets the scene and, to keep things simple, I'll present everything in wheel rates and also assume symmetry. I'll assume linear springs and bars, too. For any NASCAR / oval racers reading this, the asymmetric case is a super set of this.

Our terms will be as follows:

k_f = front spring rate (N/m)
k_{rf} = front roll bar rate (N/m)
k_{tf} = front tyre spring rate (N/m)
tf = front track (m)
k_r = front spring rate (N/m)
k_{rr} = front roll bar rate (N/m)
k_{tr} = rear tyre spring rate (N/m)
tr = rear track (m)
tm = mean track(m) (equivalent track at the c of g)
h = c of g height
rcm = mean roll centre (equivalent roll centre height at the c of g)
ϕ = roll angle (rad)
w_f = differential wheel displacement at the front (m)
w_r = differential wheel displacement at the rear (m)
F_{yt} = total applied lateral force (N)

Crunching the numbers here makes things very interesting. Again, assuming symmetry, the result can be shown as in **equation 13**.

Our next step is to tie in wheel movement with roll movement. Since the force on the front spring will be the same as the tyre, we have **equation 14**.

Similarly, at the rear we have **equation 15**.

Just to be clear, I've taken the absolute value of roll angle in **equations 14** and **15**. If we substitute **equations 14** and **15** into **equation 13**, we can now solve for the roll angle. Doing the algebra, it can be shown in **equation 16**.

At this point you might be thinking that's all great, but how do you actually use this in practice? To quote Joker from *The Dark Knight*, how about a magic trick? For that, we have **equation 17**.

Here, $roll_f$ is the differential of the front damper displacements divided by two, and $roll_r$ is the differential displacement of the rear dampers divided by two. Again, this is all at the wheel and, once again, I'm taking the absolute value of roll angle.

The reason I presented the roll proof again is twofold. Firstly, it shows you how you use the beam pogo stick to maximum effect. Secondly, it shows you the back story of where the magic number derivation comes from, and that is very significant.

Conclusion

In closing, the first key to understanding vehicle dynamics is to understand your tyre loads, and what drives them. The beam pogo stick model visualisation and the quarter car model provide us with this firm basis. As we saw in the bump steer example, it also goes a long way to explaining what you see on a race car vs a road car.

Finally, the roll angle derivation, and magic number derivation, shows you the manner in which a car generates load.

In part two of this series next month we will introduce some simple tyre models and the equations of motion to help you connect the dots. Stay tuned.

EQUATIONS 13-17

$$-F_{yt}\cdot\frac{(h-rc_m)}{2}=0.5\cdot tf\cdot(k_f+k_{rf})\cdot(0.5\cdot tf\cdot\phi-w_f)+0.5\cdot tr\cdot(k_r+k_{rr})\cdot(0.5\cdot tr\cdot\phi-w_r) \quad (13)$$

$$(k_f+k_{rf})\cdot(0.5\cdot tf\cdot\phi-w_f)=k_{tf}\cdot w_f$$
$$\therefore w_f=\frac{0.5\cdot tf\cdot\phi\cdot(k_f+k_{rf})}{(k_f+k_{rf}+k_{tf})} \quad (14)$$

$$w_r=\frac{0.5\cdot tr\cdot\phi\cdot(k_r+k_{rr})}{(k_r+k_{rr}+k_{tr})} \quad (15)$$

$$\phi=\frac{-2\cdot F_{yt}\cdot(h-rc_m)}{tf^2\cdot(k_f+k_{rf})\cdot\left(1-\frac{k_f+k_{rf}}{k_f+k_{rf}+k_{tf}}\right)+tr^2\cdot(k_r+k_{rr})\cdot\left(1-\frac{k_r+k_{rr}}{k_r+k_{rr}+k_{tr}}\right)} \quad (16)$$

$$0.5\cdot tf\cdot\phi=roll_f+w_f$$
$$0.5\cdot tr\cdot\phi=roll_r+w_r \quad (17)$$

IN BRIEF

Manufacturers competing in the **LMDh Prototype** category will be able to run brake-by-wire systems when the cars first race in 2023, according to reports. The system will be introduced along with other measures designed to restrict the advantage of running four-wheel-drive systems in Hypercar, such as reducing the options for differential settings.

Ferrari's Hypercar programme will be run by Amato Ferrari's **AF Corse** team in the FIA World Endurance Championship.

AF Corse has a long association with the marque, having first run the **Maserati MC12s** in their development phase in the FIA GT Championship. Since then it has run Ferraris in endurance and sprint racing, primarily for customers, but also with factory blessing in the FIA WEC.

McLaren has confirmed it will enter the Extreme E series for electric off-road vehicles. The car will by run by a team external to the F1 operation, limited to one engineer and four mechanics on site, as per the regulations. The team will compete in the five-race global championship in 2022.

The **Intercontinental GT Challenge** will incorporate only three rounds after the organising SRO body elected not to replace the race at Suzuka, scheduled for August.

The series kicks off at Spa in late July, before an 8-hour race in Indianapolis mid-October and Kyalami early in December.

Seat manufacturer, **Recaro**, has become an official partner to the **IMSA** racing series. The move will allow it to introduce and reinforce the merits of seating technology to a wider audience, both inside the IMSA paddock and with IMSA fans and motorsport enthusiasts worldwide.

Recaro Automotive will connect with all 18 manufacturers involved in IMSA's racing series.

Czech car manufacturer, **Praga**, has opened a 700m² facility at its UK HQ near Oulton Park. The high-spec hub will act as a global brand centre for Praga's real-world motorsport and sim' racing operations.

Dakar part of FIA World Championship

The Dakar Rally could become the ultimate proving ground for new and experimental sustainable technologies in motorsport and transportation

The Dakar Rally, one of the most famous in the world, has fallen under the auspice of the FIA, which granted World Championship status to cross country rallying.

Following an e-vote by FIA World Motorsport Council members in June, the World Championship will be launched in 2022 with an agreement with Amaury Sport Organisation, who will become the exclusive promoter of the championship for a five-year term.

The FIA is also developing technical regulations for new, alternative and experimental technologies within the already gruelling discipline. This, it is hoped, will prove to be the ultimate challenge for the application of science as the Championship will visit some of the most remote and harsh environments on the globe.

The 2022 calendar will kick off with the Dakar Rally, and the full line up of events will be released later this year.

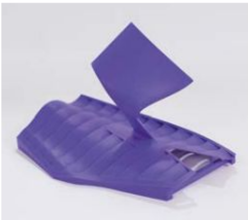
Competition will still be open to T1, T2, T3 and T4, while the FIA will publish regulations for T5 Prototype Trucks in 2022, ensuring the inclusivity of all vehicle categories for professionals and amateurs in the World Championship.

This is the seventh series to be awarded World Championship status following Formula 1, World Rally, World Endurance, World Rallycross, Formula E and Karting.

Tunnel vision

3D Systems has produced a new material specifically designed to address PIV testing applications used in motorsport wind tunnel testing. The material is called Accura Composite PIV and has been designed in collaboration with the Alpine F1 team to improve the accuracy of reading 3D printed parts in the wind tunnel.

The company's SLA technology has allowed F1 companies to build rigid aerodynamic parts with high productivity and leverage innovations such as integrated pressure tappings. These parts are used in testing that relies on a laser-based technology known as 'particle image velocimetry', or PIV.



Designed to reduce reflection, Accura Composite PIV is a major advance for wind tunnel testing

One challenge with taking reliable PIV measurements is the reflections of laser light from background surfaces other than the airborne particles. This reduces image quality and results in a loss of useful information.

Accura Composite PIV is a reflection-mitigating SLA material, which is helping aerodynamicists gain a greater insight into the aerodynamic characteristics of the wind tunnel model.

In addition to Accura Composite PIV's unique colour, the material has a high tensile and flex modulus, together with a heat deflection temperature of 100degC, making it ideal to withstand the rigours of wind tunnel testing.

The material is formulated for use with 3D Systems' stereolithography 3D printing technology that is designed for rapid production of large, high-resolution parts up to 1500mm in length.

GTD goes Pro

The US IMSA series has confirmed the technical details of its new GTD Pro category that will debut next season to replace the GTLM class cars. The series confirmed earlier this year that it will end the category for GTE-spec cars at the close of the 2021 season, following the withdrawal of Porsche and BMW, who will focus only on the long-distance races this season, leaving only Corvette.

IMSA introduced the full-spec GT3 cars in 2016 for non-professional drivers but, once it became clear there would be no new GTE class cars coming, organisers announced that the GT3 cars would also be used by all-professional line ups from Daytona in 2022.

Both Pro and Am classes will use the same S9M tyre from Michelin for the 2022 season, although a longer-term solution will be sought for 2023 onwards. Balance of Performance will use the same process and the same metrics across both classes, but the settings will be different to reflect different driver ability.

GTD Pro will adopt current GTLM sporting regulations on driver ratings, qualifying and grid placement, as well as race procedures.

GTD will remain in its current format with the same qualifying criteria, that the Silver and Bronze drivers set the team's starting position while the driver change for the second qualifying session will score points.

GTD Pro will adopt the same testing limits as the existing GTLM class, which allows for eight days. The GTD class will continue to be capped at four days, although Bronze drivers may have unrestricted test days with IMSA approval. Wind tunnel and straight-line testing is banned in GTD.

'Our technical team was thorough in its analysis and the end result allows us to chart a successful course for the future of factory-supported GT racing in GTD Pro, as opposed to the customer nature of the GTD class,' says IMSA president, John Doonan. 'Ultimately, the market will speak, as manufacturers confirm plans to participate, but we are very optimistic we will have strong fields in both GTD Pro and GTD starting next year.'

Greener goals

Greenpower Education Trust and its long-term partner, Siemens PLC, have launched a competition that tasks young people to choose from five of the 17 UN Sustainability Development Goals in the construction of a racecar.

Contenders may consider build materials, power supply or project longevity as part of their planning. The category is open for three age categories: 9-11; 11-16; 16-25. For further information, contact Reece Mowlem at greenpower@sqn.agency.

KiBox of tricks

Kistler has launched the second generation KiBox2, a new and completely redesigned measurement system for combustion engine development.

The new version features the latest advances in connectivity, useability and software, with the capability to meet the needs of powertrain analysis of IC, electric and hybrid power units.

Running of the Bulls

The Lamborghini SCV12, an exclusive, limited edition trackday car with Hypercar safety standards

Lamborghini has presented the final version of its SCV12, a trackday car built to FIA Hypercar safety standards, but has yet to confirm a full race programme for it. The first delivery of the car into customer hands took place in April, and track activity started at the end of June.

The SCV12 features a carbon chassis produced at the company's headquarters in Sant'Agata Bolognese. It has been subjected to full FIA homologation, including both static and dynamic tests.

The engine and gearbox are mounted in a cradle, the latter of which has a load bearing and structural function that helps the chassis to achieve a 20 per cent higher torsional stiffness compared to the Huracan GT3 EVO.

Meanwhile, the Italian constructor has presented its new Huracan Super Trofeo EVO2, which features revised aerodynamics, bigger front brakes and more serviceable bodywork. The car made its public debut at the end of May and costs €250,000 (approx. $297,200) excluding taxes.

IN BRIEF

The **Goodyear Tyre and Rubber Company** will complete its merger with **Cooper Tyres** in the second half of 2021, after the latter's board approved the proposal in April. The combined company will have approximately $17.5bn in *pro forma* 2019 sales.

The transaction will expand Goodyear's product offering by combining two portfolios of complementary brands.

Fischer Connectors has been awarded two prestigious Red Dot Awards for Product Design, the Mobile Phones and Tablets and Wearables category, and the Smart Products meta-category. The prizes were awarded for the Fischer LP360 connectors, taken from the Fischer Freedom Series which has already won numerous industry awards, the company tells us.

Williams team principal, **Simon Roberts**, has left the team after just 12 months in charge since Dorilton bought the venture. **Jost Capito**, who took over as CEO at Williams earlier this year, will replace him as team principal and plans to merge the race and factory-based engineering programmes under the guidance of **Francois-Xavier Demaison**.

Following a now well-established route to introducing bio-fuels, the **European Truck Racing Association** announced it will introduce 100 per cent renewable HVO bio-diesel as 'a short-term objective,' according to a press release.

The fuel will be supplied by TotalEnergies, becoming the first FIA-regulated competition to do so. HVO stands for Hydrotreated Vegetable Oil and is a premium fossil-free diesel product made from 100 per cent renewable raw materials, which does not release any new carbon dioxide into the atmosphere.

Telemetry company, **Control**, has opened an office in Davidson, North Carolina as part of its global expansion. **Richard Hull**, who joined Control as VP of sales in November, heads up the new office that will support the company's North American customers. Control has a long-term plan to build its own engineering competency.

Interview – Markus Flasch

Flasch back

BMW confirmed it will return to Prototype endurance racing with a car built to compete in IMSA. The manufacturer's CEO of M competition explains why

BY ANDREW COTTON

We are looking at WEC and Le Mans, but the only thing we want to confirm today is the IMSA series

BMW has added its name to a growing list of manufacturers that will compete in the LMDh category in North America. The German marque will compete as a two-car factory team in IMSA's WeatherTech Sportscar Championship in 2023, starting at the Daytona 24 hours.

It will join already confirmed LMDh programmes from Acura, Porsche and Audi, with General Motors and others, including Lamborghini and Lexus, currently waiting in the wings.

The announcement came in unconventional form, with Markus Flasch, the CEO of BMW M posting a picture of Jenny Holzer's V12 LMR art car on stage in a theatre on his Instagram page, along with the headline, 'We are back, Daytona 2023.' More details emerged in the press release that came out the following day, namely that this is a North American programme in the first instance.

'It is a BMW M Motorsport programme, and we forwarded to get the clearance from the board,' says Flasch. 'The markets, not just the North American market, are on board and have influenced this decision. We are looking at WEC and Le Mans, but the only thing we want to confirm today is the IMSA series. America is our most important market for BMW M. It is too early to rule other series out.'

A factory team in IMSA makes perfect sense in the wake of Acura and Mazda both running well-funded programmes in the US since the start of DPi in 2017. That said, Cadillac has relied on customer teams and found considerable success.

In a surprising move, BMW M announced its intention on social media platform Instagram, with the somewhat enigmatic posting of an LMR art car shown above

Mazda, meanwhile, has elected to withdraw from the series and so partner, Multimatic, has agreed with the VAG group to supply both Audi and Porsche.

Chassis partner

BMW has not yet made public its decision on chassis partner, with four to choose from by regulation. With Multimatic confirmed to supply the 'spine' for Audi and Porsche, ORECA likely to continue with Acura, and with Ligier involved in the Peugeot LMH programme, it is rumoured that BMW will partner with Dallara, taking the lead in the development of the chassis as GM has yet to confirm its plans.

'We have not announced the chassis manufacturer for the programme, and I am not aware of the other manufacturers and who they are linked to, but we will announce the chassis manufacturer in the near future,' confirms Flasch. 'We are well ahead in our development, and the meaning behind the announcement this late does not indicate we are late for the return in 2023.

'I think I am safe [to say] we will be successful in Daytona in 2023.'

Taking a chassis manufacturer that is not yet confirmed with another OEM means BMW can influence the design of the base tub, and specify key requirements such as the cooling system and suspension pick-up points to suit its own design.

The company is, says Flasch, well advanced with the design phase, and the car will be out on track testing next year.

'We know what we are doing. The engine exists, [though] we need to modify it, it is not on the dyno yet. Designs are almost there, exterior designs, and this is all I can say at the moment.'

Production basis

The engine will relate closely to the high-performance production engines that will be fitted to M-series road cars in the near future. The twin turbo, 3.0-litre, inline, six-cylinder S58 engine that is fitted to some of the company's production 'competition' models is almost certain to be the basis.

'It is too early to confirm the engine concept, but you can assume we won't do anything from scratch,' notes Flasch. 'Whatever we bring will have some context to what we will see on the street in this time period.'

The LMDh concept uses the base of an LMP2 car, including the tub, suspension pick-up points and gearbox, but power for the top class will be supplemented by a mild hybrid system that is spec across all cars. Under the LMDh regulations, a manufacturer will supply its own engine (unlike LMP2, which currently relies on a spec Gibson engine) and aero, designed to suit its own styling cues, as well as provide cooling for the different engine concepts.

The spec hybrid system, announced earlier this year, follows the whole philosophy of LMDh racing in that it is designed to reduce cost to teams and manufacturers, which is one reason why they are jumping on board with such relish, but it's not something the LMH constructors can quite fathom. The LMH concept is that all aspects of the build are down to the manufacturer, including chassis, engine, hybrid system, brakes and suspension. Although this option is more costly, it puts the manufacturer firmly in control.

'Of course we have made a conscious decision,' says Flasch. 'We investigated the opportunities in LMH, but came to the conclusion that the LMDh car, and the way the specification book is written for it, far better fits our approach to motorsport, and what we want to achieve.'

Customer racing?

That could mean customer cars then. One of the key elements of GT3 racing is that the companies build strong customer bases, including a robust support system for their teams wherever they are racing. Although BMW would be able to support customer LMDh programmes, it has not decided yet whether or not to do so, though it seems highly likely if they plan to take the cars to Le Mans in the future.

'There is a lot of chance to [run] LMDh as a customer racing programme,' says Flasch. 'We have not yet decided on it, but I like the idea. We have announced that we will go for two cars to start with for one team [in IMSA], and the further future is to be decided.

'This is dependent on WEC, and also upon whether or not we do a customer programme.'

It is hard to see a company such as BMW *not* racing its

We are well ahead in our development, and the meaning behind the announcement this late does not indicate we are late for the return in 2023

Prototype at Le Mans, likely in factory hands as well as customers', but the performance balancing needs to be stable across LMDh and LMH before a final decision can be made, and those details are still unconfirmed.

Electric future

The decision to head into a mildly hybridised racing category such as LMDh came after BMW confirmed its withdrawal from the all-electric Formula E championship. This all fits with the growing feeling that electric cars are for mobility, not for sport, but Flasch denies this is the case. There is, he says, a plan for a full electric sport M range in the future, and powerful hybridisation is a stepping stone towards this future.

'It is not an either / or question,' he says of the choice between electric and hybrid. 'The future for BMW M will be electric, and there will be a transition period [in which] we will have high performance hybrid cars.

'My approach is that in the first place it needs to be attractive to the fan community and have a positive impact on the brand, and secondly it needs to transport a technical vision, but not the other way around. I am not looking for any series just to promote a technical vision and then afterwards answer the question if it is attractive to a fan to buy a ticket, or switch on the TV.

'I am 100 per cent confident that the LMDh concept is the right racing series in that time frame. The engine we will have in this car will have a close association to what we will have in our street legal, high-performance cars, and we are closely investigating full electric platforms.'

This could be a GT concept, with the ITR looking to take the DTM series to an electric platform, while the FIA has recently launched the idea of an electric GT championship, although no manufacturer has yet signed up to that. Could BMW be the first?

'I know we will have an electric future at BMW M, and we have vehicles in development that will push the limit from what we know today. This is highly attractive to our high performance customers,' confirms Flasch. 'I do think that there is a future in racing for fully electric cars, but at the right time and only if the format is also attractive to the fans.'

The company was instrumental in guiding the ACO and the FIA towards hydrogen under the previous director, Jens Marquardt, but Flasch admits there are no immediate plans for a hydrogen Prototype, despite there being a category for it at Le Mans in the near future.

'We have looked at it, and there is no concrete project in this direction at the moment.'

Development phase

The M4 GT3 will carry the manufacturer's works-supported customer racing programmes for the next few years, with the car in its final development phase ahead of sale to customers for Daytona in 2023. It will compete in various races this year and next before the first cars are delivered to customers.

The headline event for the GT3 category is the Spa 24 hours, held at the end of July, but there is talk of the cars going to Le Mans to replace the outgoing GTE cars. This, says Flasch, had no bearing

GT3 is for us an international and valid platform, and whether or not the car will be seen at Le Mans would not change our decision

Markus Flasch shares a joke with BMW legend Jochen Neerpasch

BMW is the latest manufacturer to have launched its next generation GT3 car, the all-new BMW M4 GT3, but Flasch is confident that costs will not explode even if the cars go to Le Mans

The future for BMW M will be electric, and there will be a transition period [in which] we will have high performance hybrid cars

on the development of the new M4 GT3 racer.

'GT3 is for us an international and valid platform, and whether or not the car will be seen at Le Mans would not change our decision to develop a GT3 car anyway. I don't know if it is going to happen or not and right now I don't want to speculate.

'Our customers are racing GT3 cars today without Le Mans, and they like what they do. And now we bring them a *better* GT3 car. Can it be better? Yes, there can be one more race on the calendar but, if not, that wouldn't change the game.'

Pushing the envelope

He dismisses the idea that the higher value race, Le Mans, would encourage manufacturers to push the design envelope within the new rules that are open to them. They are able to build what they want on the basis that the performance balancing system will be effective, rather than having their options limited by a committee based on what shape and type of car and engine they started with.

'I don't think that this is going to happen,' concludes Flasch. 'The manufacturers will look at keeping cost levels as they are today, and I don't think that this is going to explode.'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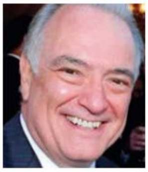

Efficiency drive

In conversation with Andy Cowell

Andy Cowell, the former managing director of Mercedes AMG's high-performance powertrains, spent time at Cosworth and BMW in F1 before joining Mercedes-Ilmor in 2004. From 2013, he oversaw the creation of the V6 turbo-hybrid power unit, which made Mercedes the dominant force in Formula 1 by winning seven consecutive double World Championships.

What role can F1, and motorsport engineering, play in the next decade of global climate challenges and energy efficiency?
Bill Gates is inspiring when in his book, *How to Avoid A Climate Disaster*, he says; 'Achieving net zero will be humanity's greatest ever achievement… the solution isn't to stop driving, flying or doing all the things we do today – it is to innovate'.

Quick, competitive innovation and effort on a scale the world has never seen, and with time critical deadlines, creates a perfect opportunity for the UK's Motorsport Valley.

I've spent 30 years on an annual quest to win races and championships, knowing only the winner gets to enjoy that singular success. The innovative environment of F1 is fuelled by an innate, primal desire to be that winner. It's a continual drive to create ideas that reduce lap times, and then developing and introducing them quicker than your opponent – motorsport really is that simple.

A diverse range of capabilities and engineers cover combustion efficiency, thermodynamic, mechanical, electrical and hydraulic efficiencies, simulation, design, materials, manufacturing, build and test facilities with great suppliers. All work in an environment that allows no distraction from their crucial core work, and every aspect is obsessively studied to gain better understanding and generate new ideas to improve efficiency.

Some describe the outcomes as miraculous, but they're not. There's no 'unobtanium' used, they're the result of relentless, obsessive hard work. To deliver 50 per cent+ thermal efficiency from a highly transient, hybrid internal combustion engine is good going. The whole supply chain can be proud of that achievement.

How influential was the introduction of KERS, with electric drive, hybrid technology, in 2009?
We had zero experience of high voltage systems at the time and were allowed no additional weight. The whole system had to weigh less than 28kg and deliver the full 60kW at 400kJ per lap. A clear but tough technical target, combined with a challenging, first-race time target. These make up a BHAG (big hairy audacious goal), an essential for driving innovative projects.

The goal was achieved through rapid learning from industry experts. We also relied on that fundamental premise of all innovation – never give up. Proof that motorsport is a mighty innovator of energy efficient systems is that the industry now builds four F1 PUs delivering close to 50 per cent thermal efficiency.

XPB

There's no magic formula, says Cowell, genuine innovations are the result of relentless, obsessive hard work

The real magic, though, is to quickly turn crazy ideas into real hardware that fits together and works efficiently. Every step of the value chain is understood, owned and controlled by the industry. As a result, Motorsport Valley UK has become a very impressive, extremely capable, global innovation community.

What lies ahead when road cars will be mainly EVs? Where will all the electricity come from?
EVs are highly energy efficient, with low drag and lightweight construction compensating for battery mass, low-loss control systems and human interfaces. To accelerate innovation, we should transfer, and demonstrate widely, motorsport's energy-efficient capabilities.

The need is for clean, zero emission electricity. Last year, about 45 per cent of UK electricity achieved this. A three to four-fold increase in capacity from a green generating industry is required and there's a lot happening already – more wind turbines and solar panels in use.

The ICE will continue, in the short term, being used by a very large existing fleet of cars. However, there will be no suitable electric solution for aviation and heavy-duty transport. Both those need carbon neutral, synthetic fuel.

Motorsport, especially F1 with its high power, high duty cycle formula, will play a significant part in these innovation journeys.

So what are your crazy ideas for a future Formula 1 powertrain?
It would still use a fuel, a petrol-type hydrocarbon, but manufactured from carbon captured from the atmosphere, not pumped from the ground. All energy required to make the fuel must be declared, and be directly generated using zero emission methods. This could be new solar, wind, tabletop nuclear fusion reactor or whatever – anything but old fossil fuel.

The F1 powertrain and car would have technical regs closely aligned with industries, not specifically automotive, which could benefit from the technical solutions being raced.

As F1 is used to having materials banned, let's now focus on using sustainable materials from around our globe – specifically in battery, inverters and electric motors.

The world needs such innovations swiftly turned into reality, another motorsport speciality.

What, then, should businesses include in their strategic plans?
Set tough, ambitious targets based on good, honourable innovation – not just planting trees. Aim for it to be a big achievement, and quickly delivered – we are in a global race here.

Pick your strongest team and give them time to dedicate themselves 100 per cent to the task.

Get outside help. None of us can do new things without it. Nothing works right first time unless it was an easy project in the first place.

Finally, be brave, bold, tenacious and supportive of everybody within this unique, innovative Motorsport Valley business community. But most of all, have fun!

For more information on the MIA, check out www.the-mia.com – or contact info@the-mia.com.

To accelerate innovation, we should transfer, and demonstarate widely, motorsport's energy-efficient capabilities

Racecar Engineering
The International Journal of Motorsport Technology

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Editor
Andrew Cotton
@RacecarEd
Email andrew.cotton@chelseamagazines.com

Deputy editor
Stewart Mitchell
@RacecarEngineer
Email stewart.mitchell@chelseamagazines.com

Chief sub editor
Mike Pye

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Technical consultant
Peter Wright

Contributors
Mike Blanchet, Mike Breslin, Lawrence Butcher, Jahee Campbell-Brennan, Danny Nowlan, Mark Ortiz, Andrea Quintarelli, Claude Rouelle, Peter Wright

Photography
James Moy

Group sales director Catherine Chapman
Email catherine.chapman@chelseamagazines.com

Head of sales operations Jodie Green
Email jodie.green@chelseamagazines.com

Advertisement manager Lauren Mills
Tel +44 (0) 20 7349 3796
Email lauren.mills@chelseamagazines.com

Subscriptions manager
Luke Chadwick **Tel** +44 (0) 20 7349 3700
Email luke.chadwick@chelseamagazines.com

Publisher Simon Temlett
Managing director James Dobson
Chairman Paul Dobson

Editorial and advertising
Racecar Engineering, Chelsea Magazine Company, Jubilee House, 2 Jubilee Place, London, SW3 3TQ
Tel +44 (0) 20 7349 3700

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Printed by William Gibbons
Printed in England
ISSN No 0961-1096
USPS No 007-969

THE CHELSEA MAGAZINE COMPANY LTD

www.racecar-engineering.com

Bak to the future

Or what can we blame next for failure?

The Azerbaijan Grand Prix was remarkable in many ways, but perhaps the most startling revelation was that Pirelli bore the brunt of ire from Red Bull and Aston Martin for catastrophic tyre failures on a street circuit lined by trees.

The tyre company's subsequent report says the inner sidewalls failed, despite the teams following Pirelli's guidance, and the FIA issued a Technical Directive ahead of the French GP mid-June in which it clarified the checks it will make around tyre pressures. However, the fact remains that at Baku a number of competitors suffered cut tyres that were initially thought to have contributed to the punctures, and therefore affected the race result.

Pirelli initially surmised the failures that afflicted Lance Stroll and Max Verstappen could have been due to cut tyres, and said it found the same on Lewis Hamilton's Mercedes. The tyre manufacturer also pointed out other cars were running just fine, for longer, on the same compound of tyre at the same point in the race.

Despite Pirelli making these statements, no doubt with some evidence behind them, Mario Isola was still forced to defend Pirelli's position immediately after the race.

The teams that had the blow outs stated they had no warning, and there was no gradual loss of pressure. Both failures were sudden and unexpected, leading Pirelli to surmise in a press briefing afterwards that the reason behind them had occurred somewhere near the point of failure.

Mercedes just got lucky that the debris did not compromise the construction of the tyre on Hamilton's car, or he could have been another suffering a blow out. That much we did know, or at least, there was no reason to doubt Pirelli's word, yet teams were not happy.

Interestingly, early in the race Red Bull had warned Verstappen to take care of his left rear tyre although, according to Pirelli, that was not the most stressed tyre of the four on the car. That accolade belonged to the right rear so why was Red Bull so worried about the less stressed of the two rear tyres, particularly as it had followed all of Pirelli's guidance and protocols before the race?

The desire to lay blame on the tyre constructor is nothing new. Teams are constantly pushing the boundaries and taking risks with tyre set-up, and then pointing the finger at the supplier when there is a failure. The tyre supplier than applies to have maximum settings to protect its product from extremes. Pirelli has had the same before, with teams swapping tyres from left to right, and in GT racing particularly, with Audi and Lamborghini running extreme camber settings and pressures, and then demanding Pirelli produce a tyre to cope with such settings. At which point they go even more extreme.

The TD issued by the FIA suggested four points that would be better monitored from the French Grand Prix onwards. The first was that cold tyre pressures would be taken using a gauge calibrated at, or by, Pirelli, and sealed by the FIA. What were they using before?

Pressure cooker

The second was that delaying the release of a car from the garage would also be considered poorly. Once again, this suggests that tyre pressures were the root cause of concern. Further to this, cold pressures *will* be checked (a change of wording from 'may be checked') after running on used tyres, pressures once again a focus of attention.

Another new check is the maximum temperature within a tyre blanket, which suggests teams were overheating tyres and then cooling them before the car went out on circuit. Air expands, so the correct pressure at temperature is going to drop as the tyre cools, which is what the teams are after.

> **The desire to lay blame on the tyre constructor is nothing new**

It was the fourth, though, which was slightly baffling. The TD suggests teams may have been playing with the moisture content of the gas within the tyre. Not a new trick.

So, as the teams have confirmed they were running within Pirelli's protocols, and these protocols didn't even cover the basics of what a team is able to do to affect performance, what went wrong? I suspect the teams pushed back on items Pirelli wanted to control, then pushed the tyres to the limit within what they were not forbidden from touching, then suffered failures which changed the outcome of the race, and blamed Pirelli.

There are a few points to consider here. One is that tyres *will* get cut on a street track lined with trees and this is clearly a risk to the cars. Rather than stipulate tree surgery before a grand prix, teams need to accept this natural risk.

The second point is that teams will *always* play with their tyres. The entire car is set up to get the most out of the tiny contact patch. The question is where should the line be drawn, and where should teams be given freedom? Clearly, not at the point the tyre fails, but where is safe?

To use a phrase coined by Peter Wright, you have to move the cars away from the edge of the table, and with the TD, the FIA hopes it has done so before some really quick tracks come up on the F1 schedule.

ANDREW COTTON Editor