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November 2020 • Vol 30 No 11 • www.racecar-engineering.com • UK £5.95 • US $14.50

Le Mans triple crown

Toyota's TS050 seals outright win again

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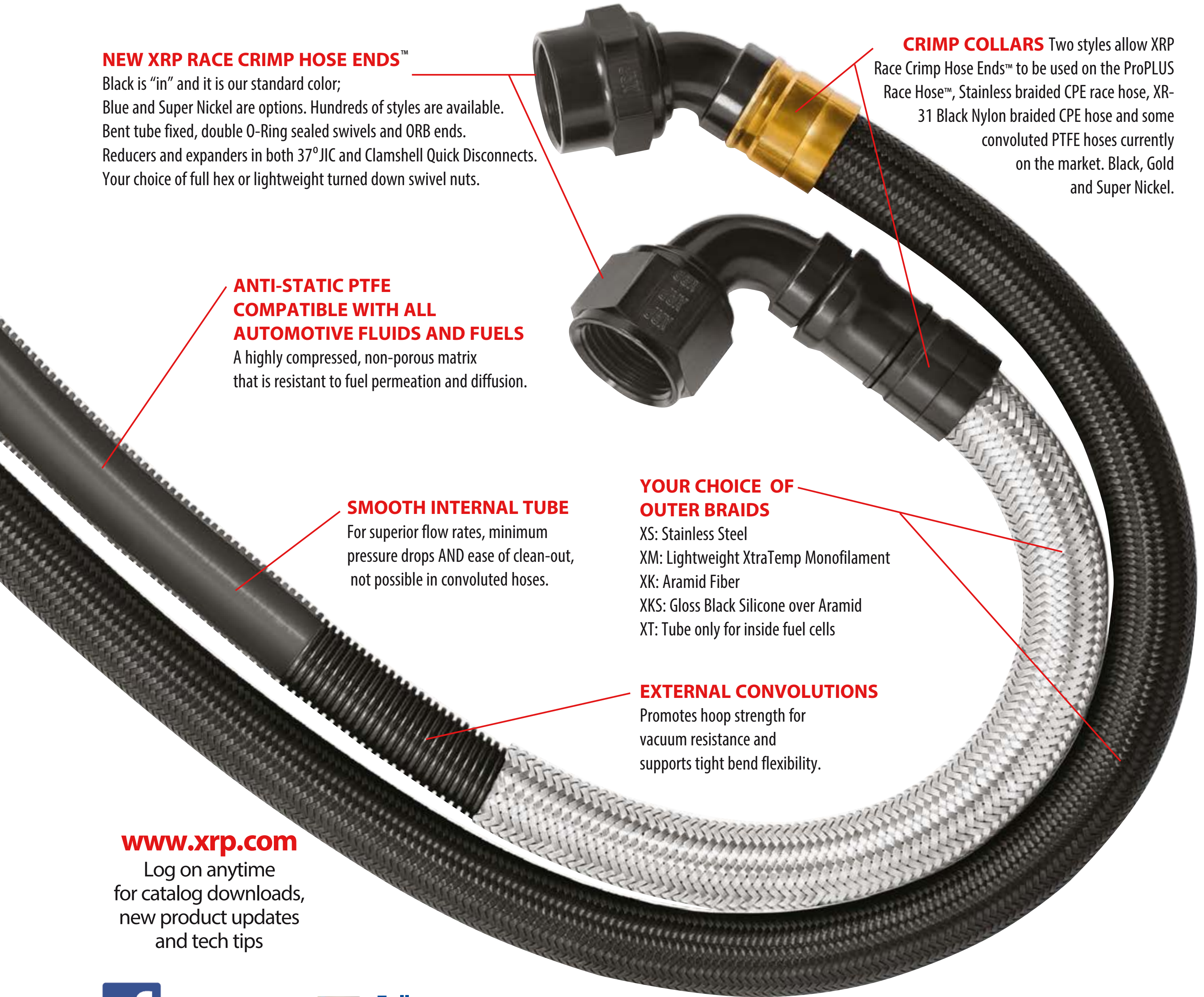

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TECHNICAL

Competing in the Silver category for young drivers, Steven Palette and Simon Gachet won the GT World Challenge Europe Sprint race at Magny Cours in the Sainteloc Audi the week before Le Mans. Not bad preparation for the Spa 24 Hours in October

Prep school

How condensed schedules are putting added pressure on teams

Earlier this year I wrote a column on how IMSA had put restrictions on the number of personnel allowed at the track this year due to the pandemic. Limited to 15 team members per car, we had gone into Daytona not knowing anything different as that was all we had anyway. We hadn't had to reduce our numbers because we already run a lean team, so were able to make the best of it and performed pretty well. But if you are used to having 30 people per car it's more of a challenge. You have to think about which jobs to cut out, or work out who can do two jobs, and what they should be.

We are now allowed a team of 35 people, but that's the full team. We are a few races in and this is when it gets hard. The same people have been working on the cars between events as we have had to run a lean ship back at base because of all the travel restrictions. Because racecars require a lot of attention to detail, that small team has to work incredibly hard. Now, when we get back to the shop after an event, the same team that has just worked the race has to strip back the car to analyse everything from a lifing perspective.

You also have to fine tune everything because the cars take a battering at the racetrack. Bodywork is damaged from stone chips, contact or kerbs and it all needs to be fixed before the next race.

Michael L. Levitt

Racecars are like young children, unpredictable and require a lot of looking after

Three in a row

During the run of three races in June, we just had to get it done. We would come in on the Monday morning after the race event and work flat out until the following Saturday, when we went racing again. We had a number of things pre-prepped, in terms of gears and ratios and so on, and we had assistance from Xtrac on that front so at least that was pretty straightforward.

However, after those three races the cars had covered quite a few miles. And then we went straight to Road Atlanta for a six-hour race, and came back with a lot of work to do!

Again, we had to go through the bodywork. Things move in race situations and, if your wing angle has changed, then maybe you have a slightly damaged end plate. Things like that all need to be checked and re-jigged, and it all takes time. With aero parts you have to be so precise in how you build them so there is no difference, part-to-part, when you put them onto the car. And no difference car to car.

If you have different people setting up bodywork there is always something that can go wrong. Is a bolt head flush with the bodywork? Is the angle of the carbon part that attaches to the floor at exactly the same angle between both cars? There are lots of differences, so we have jigs, tolerances that have been set and drawings to say how everything needs to be put together, but still someone needs to do it.

We spend a huge amount of time refining all of those little details to make sure the cars are even from race to race. But then the no.77 car in Atlanta decided to put oil all over itself, the pit lane, the track and the paddock. It was a massive oil leak. We had to do a lot of investigative work to find out what happened, and *why*. It was a rare occurrence, not one we had experienced before, but that happens a lot on racecars.

Expect the unexpected

Wherever you go, be it a 2h40m race or a 24-hour race, or anything in between, there will always be something new come up that you haven't seen before. That's just the nature of racing. You find things you least expected.

A good example of this is Toyota at Le Mans this year. Think how long that car has been going for, how much testing that team has done. If they didn't find it in two durability tests on track, and in dyno tests in a workshop, then there will inevitably be questions when something unexpected happens in a race. Why did that occur? Was material tolerancing out? Was the fitment incorrect? Was there incorrect strain on different fixations?

Prototype parts

In Prototype racing, you are working with a small number of parts that have been made specifically for one function. These are not mass produced parts. As such, there will always be small differences that can cause small issues which, in the case of the no.7 Toyota at Le Mans, cost the car the win. Again.

As a side note to that, a performance engineer at Audi I was talking to said the fastest car never wins at Le Mans. Bear in mind there is fastest lap, and fastest average. At each Le Mans, it is almost written into the rules that if you have the fastest averages, the chances of your car finishing on the top step of the podium are so tiny it is ridiculous.

The condensed schedule puts even greater pressure on teams than were already there. The schedules IMSA has created over the last few events have tried to minimise the time crews are at the track and, where possible, fit everything in, from unload to race, in just two days. That's a tough call for the teams running Prototypes as you need time to prep the cars between sessions. There is never enough time when you have a full, regular crew at the track and back at base, but when you have reduced numbers it becomes harder still. Factor in the travel schedule to and from races and you start to realise the intense pressure on teams the Covid pandemic has brought in all forms of racing.

With four races to go, this is the time we really have to dig in. It's going to be a hard championship fight that tests us all to our limits but that is the nature of racing!

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

You have to think about which jobs to cut out, or work out who can do two jobs, and what they should be

Beauty in the beast

Aesthetics aside, are F2 and F3 drivers being set a bad example?

Time was, for those who appreciate form that follows function, creativity and, yes, even sculpture, racing engines were objects of beauty. Even inanimate, without the adrenaline fix of their sound and fury, they could make one pause a breath or two with wonder and nod with appreciation at their concept and fine engineering.

Gleaming cam covers with multiple inlet trumpets standing proud between them, superb castings and forgings, purposeful-looking superchargers, even machine-turned cylinder blocks – all stand out as examples of manual rather than digital manufacturing skills. Think of pre-WWII Alfa Romeos, Bugattis and Mercedes-Benz engines. Post-war, a racing straight six, be it from Jaguar, Aston Martin or Maserati, still today encourages a bystander to take time and study it. The 1.5-litre Coventry Climax and BRM V8s of the 1960s were little jewels.

Compactness was a highlight of Cosworth's DFV, leading eventually to the amazingly light but powerful pre-hybrid V10 F1 units, all as pleasing to the eye as the ear.

Piled on top

So often now, however, particularly with the increased adoption of hybrid power in Le Mans Prototypes and F1, it's difficult to even *see* the engines. All the paraphernalia of plumbing, wiring, monitoring and control devices, not to mention turbos and exhausts and all their associated heat shielding, is piled on top, for aero reasons.

Even out of the car, if fully dressed, the impression given is that the engines are merely another component. A force-fed pump activated by internal combustion. Of course, that's what engines, racing or otherwise, have always been, but never before have they seemed to play such a subservient visual role.

Inevitable really, given the progress of technology, but a bit of a shame. At least, thankfully, they remain more interesting to look at than an electric motor and battery.

Aesthetics aside, when F3 departed from the decades-long concept of 2.0-litre, atmospheric engines in small, lightweight chassis to the current breed of heavier racers with 3.4-litre engines with almost 60 per cent more power, like many in motor racing I railed against it. The new, rather dumpy, one-make Dallara cars have little to differentiate them from their F2 cousins, certainly for those less knowledgeable in such things.

In contrast, the previous Dallara designs, culminating in the F2018, were little beauties. Almost delicate in appearance and construction, together with the distinctive, bomb-shaped airbox, made them instantly recognisable.

By inevitably being more expensive to buy and run, I feared for the future of F3. The fact that, even in this pandemic-stricken world, near 30 cars have been able to regularly fill the grid maybe proves me wrong about old vs new F3. But where does all that money come from? Perhaps, in some instances, better not to ask!

Full credit, nonetheless, to Red Bull, Ferrari, Renault and others for their junior driver schemes, which have a major bearing on F3 and F2 drivers and teams being on such healthy grids.

XPB

19-year-old Australian driver, Oscar Piastri, won the 2020 F3 title at Mugello and is one of the rising crop of talented individuals to come through the ranks

Something else has impressed me of late. When F1 live TV was free-to-air, I held out against Sky. With so much other racing available, I reckoned I'd spend too much time watching the HD screen that now fills a good part of our lounge. But when live coverage became pay-to-view only, I had to relent and sign up. Well, of course, I was right. I *do* spend too much time now watching F3, F2 and IndyCar, as well as F1, often including practice and qualifying. It's become compulsive and, I admit, is a bit sad. However, what I have gained is an appreciation of the levels of talent and professionalism (with some notable exceptions!) displayed by the seemingly very young drivers in F3 and F2. In particular, the skill they demonstrate in wheel-to-wheel racing, often resembling Formula Ford 1600 in its heyday, just going a lot faster.

One must understand, of course, that with the majority of them coming from privileged backgrounds, or with supportive families making great sacrifices, these youngsters are well educated and have been immersed in racing culture since they were six or seven years of age. Many have known nothing other than competing in karts and cars all through their upbringing.

Playing the fool

In contrast, F1 drivers and their engineers / strategists make fools of themselves by being so obsessed with getting a slipstream tow in qualifying at fast circuits that they trip over each other and end up slower than if they'd just gone for a non-obstructed flying lap, picking up a tow as the opportunity presents. So F2 and F3 drivers, in turn, have done the same. The advantage gained from slipstreaming is real, but rarely works as planned. This farcical bunched-up weaving, apart from its potential dangers, impedes those drivers behind attempting to set a quick lap time. Consequently, culprits should immediately be punished by a grid drop – the regulation exists to do this, so why isn't it implemented? Do we have to wait for someone to get badly hurt before action is taken?

Also beyond my understanding is the lack of consistency in setting track limits. I could barely believe when the only limit set at Mugello was the gravel. The argument that it doesn't matter about limits as long as no advantage is gained is completely wrong. At all corners at every circuit the limit should be the same. Given the high-downforce cornering speeds of contemporary racecars, which exaggerate even a small driving error, probably the best compromise is the rule used at Monza this year whereby at least two wheels must remain on the track, as defined by the white line, at all times.

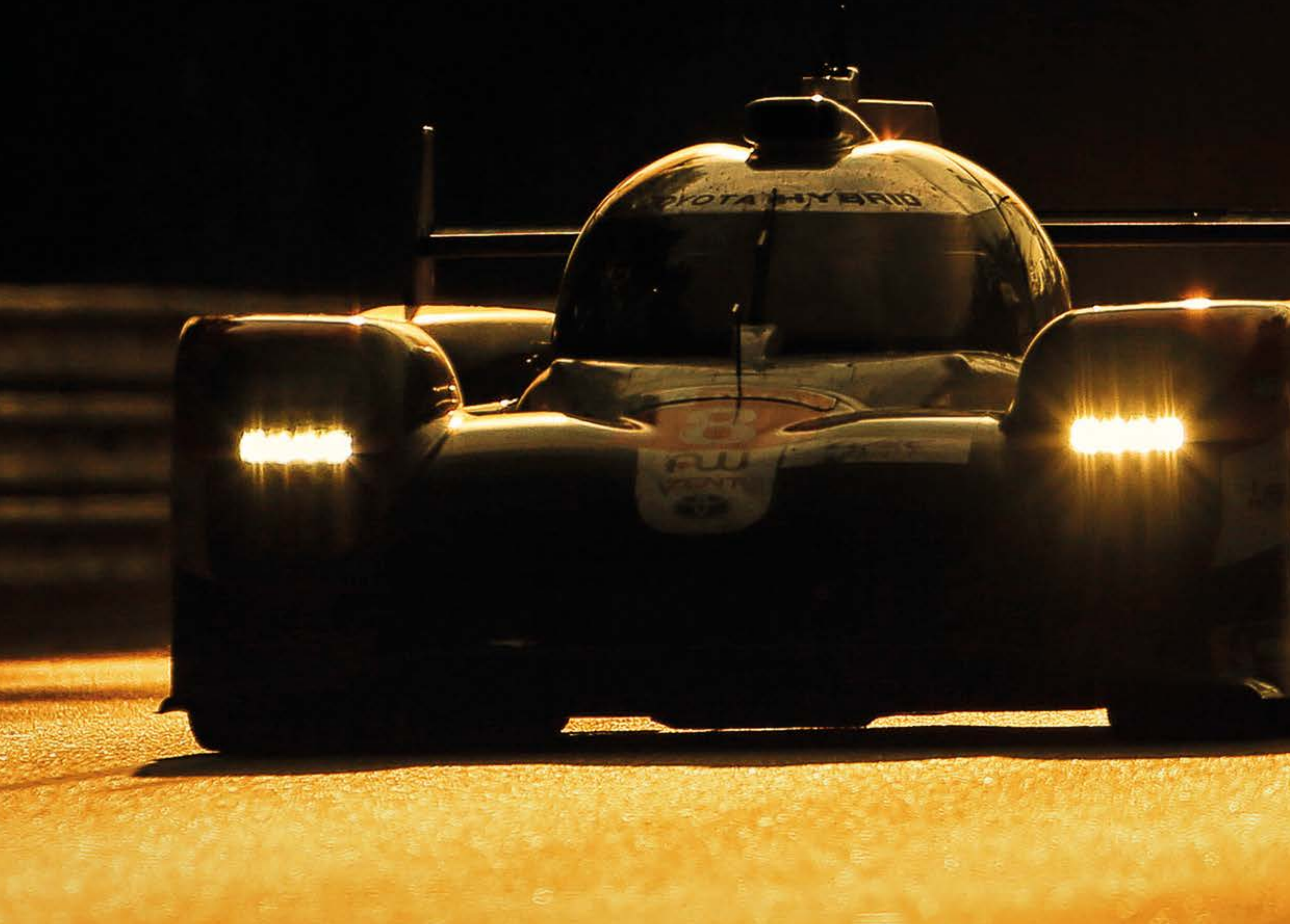
If the occupants of the cockpits cannot adhere to this, they really shouldn't be there.

Never before have [engines] seemed to play such a subservient visual role

Gold standard

Toyota took its third win at Le Mans, but not without drama, while United Autosport triumphed in LMP2 and Aston Martin in the GTE Pro and Am classes

By ANDREW COTTON



The 2020 edition of the Le Mans 24 Hours was never going to be a classic, despite the best efforts of those trying to equalise the performance. Ultimately, Toyota finished up winning the race as expected, five laps ahead of the Rebellion, as also expected, but what was unusual was the winning car spent 10 minutes longer on pit road due to a brake duct issue that lost two laps, and the third-placed Toyota had a long stop to change the exhaust manifold and turbo.

Those events should have put them within reach of the Rebellion that, for much of the race, had a trouble-free run. Other than a slightly longer stop to change the nose on Sunday, the ORECA-chassis entered by the watch maker made it through the race without fault to record a memorable podium at what was the last Le Mans for the team.

The ByKolles had another ignominious race that ended with a crash on Saturday night, Bruno Spengler spinning at Dunlop Curves. But although the car has been developed in-house, it was a long way off the pace from the start.

In the LMP2 category, United Autosport won a dramatic and fiercely fought race between two ORECA chassis, Gibson-powered cars, one on Goodyear tyres, the winner on Michelin. Strategy, speed and the ability of the third driver was key to the result in the second-tier class.

Aston Martin celebrated a double win in the GT categories, winning both the Pro and Am classes with its Vantage models. The victory in the Pro class came after extensive testing in Aragon to ensure the Alcon brakes were able to go the full distance without change. The other contenders did change at least the fronts, but further work on aero and set-up meant the Aston's rear tyres would also last a full double stint, unlike 2019.

LMP1

Although the rest of the World Endurance Championship was governed by a Balance of Performance system, the restrictions were lifted at Le Mans with the two cars from the same team starting with the same weight and fuel allowance as each other. The ACO and FIA therefore only had the Equivalence of Technology table with which it could attempt to balance the different concepts.

This table received a tweak in the run up to the race, but the upshot was the Toyotas raced with more weight than last year, up by 7kg, but were able to carry 0.1kg more fuel to compensate. By contrast, the non-hybrids raced at the same weight as in 2019 but were able to carry an extra 4.7kg of fuel, which meant they could do the same number of laps per stint as the Toyotas.

Lap times were also comparable in race trim and indeed, the Rebellion put in the fastest lap of the race, a 3m19.264s set by Bruno Senna early on. Happy hour at dawn, when the air temperature is low and the track has rubbered in, didn't bring the usual fast lap runs as by then the race was almost settled.

Toyota went into the race having qualified first and third, Senna lining up on the front row alongside Conway. While the Rebellions could match the Toyotas over a single lap, they were not able to live with them in traffic.

The hybrids' push-to-pass power delivery system meant they could dispatch the slower cars more effectively than the non-hybrids.

TECH SPEC: Toyota TS050

Chassis:	Carbon monocque
Suspension:	Double wishbone and torsion bar
Dampers:	Öhlins four-way
Brakes:	Brembo discs, Akebono pads
Tyres:	Michelin
Wheels:	Rays
Lights:	Laser
Fuelling valve:	Staubli, Krontec
Dimension:	4650 x 1900 x 1050mm
Weight:	888kg
Engine:	2.4-litre, bi-turbo hybrid, 90 degree aluminium block
Turbos:	Garrett
Oil:	Mobil
Clutch:	ZF-Sachs
Gearbox:	Xtrac

The no.7 Toyota took pole position and the team admitted it was running out of words to say to its drivers and crew after the win was denied them for a third successive time

On pace alone, the no.7 Toyota led, and the lead extended dramatically in the first hour as it hit a slow zone on the front straight once, the no.1 Rebellion twice, losing more than 40 seconds in the process. In the past, with multiple contenders for overall victory, race director, Eduardo Freitas, has focused on the LMP1 cars to ensure something like that doesn't happen, while the other classes have been ignored in that respect. This year, though, it was done on track condition alone.

The no.7 car was, for the third year in a row, the faster of the two Toyotas. Mike Conway, Kamui Kobayashi and Jose Maria Lopez once again set their car up perfectly for the conditions and, when they established a lead of more than a lap on Saturday after their team mates hit trouble, they dared to dream this could have been their year.

The no.8 Toyota of Brendon Hartley, Kazuki Nakajima and Sebastian Buemi ran third in the opening stages, but early in the second stint Buemi pitted with a left rear puncture that threw the car out of the regular pit stop sequence. The sister car, meanwhile, metronomically put in 11-lap stints that were fast and consistent, and when the no.8 car suffered overheating brakes due to debris in the brake ducts, they knew they would need a long stop to repair the damage, or risk not making it to the end of the race.

They did so on during hour seven and dropped off the lead lap altogether. In fact, they lost two laps. Their pace was consistently slower than the no.7 car, despite the drivers of that one staying off the kerbs, protecting the car and preparing for a potential fight on Sunday morning to hold their track position.

The race then settled into its natural rhythm, with the three top cars circulating together. The no.3 Rebellion had lost time with a burnt rear bodywork that needed changing, and then Louis Deletraz hit a suicidal rabbit during the night that broke the nose and splitter of the car.

At 2.40am, the race turned when the no.7 car stopped with a holed exhaust manifold. The team replaced the whole system, including a turbo, and the repair lasted 29 minutes. That was the end of their challenge for the overall win, but there was still a podium place on offer. The two Rebellions ran second and third at this point, but the Toyota had almost 12 hours to make up the necessary lap to snatch third.

That went wrong when Conway ran over debris on the track, damaging the underfloor aerodynamics and costing lap time (see the rising averages chart below). However, they were helped in their quest for the podium when the clutch on the no.3 Rebellion failed. While Romain Dumas was able to drive around the problem, it caught out Deletraz, who ran wide at the Indianapolis corner and tagged a barrier, requiring a stop for repairs.

That settled the race for the podium. Toyota's no.7 crew stood on the third step behind the no.1 Rebellion team, with the no.8 car crew victorious for the third time. Once again, it was pure luck they made it, this time with Hartley who won in 2017 for Porsche and 2020 for Toyota.

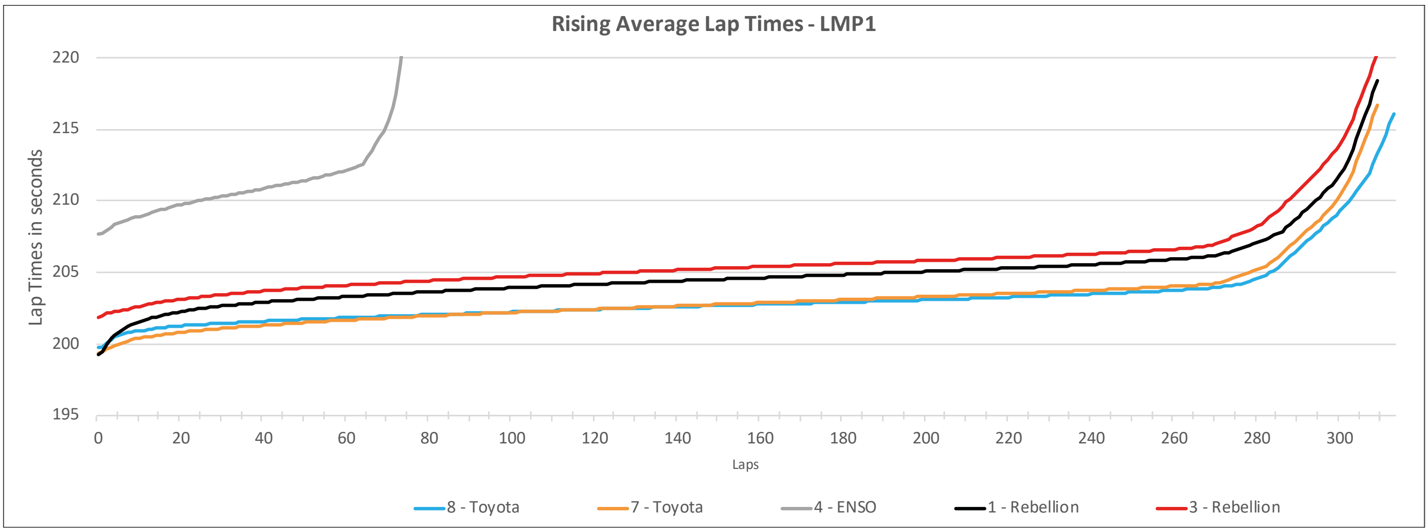
LMP2

If there was ever to be a more competitive class than LMP2, it is hard to imagine. The class featured strong teams from Europe, the US and Asia, and platinum drivers alongside golds and silvers that were not slow.

The cars have been raced for years and are proven and extremely reliable. All entries were fitted with Gibson's 4.2-litre GK428 V8 engine, the ORECAs and Dallaras ran with Xtrac gearboxes, while the Ligier was fitted with Hewland's TLS200 unit.

On paper the grid looked strong, and discounting the cars that featured bronze drivers there were more than 15 cars that could have challenged for the win (Dwight Merriman crashed his IDEC ORECA in practice and was replaced by Patrick Pilet after being diagnosed unfit to race due to back problems). With short stints of around 30 minutes, and with seven teams all lined up next to each other in the pit lane, cars pitting out of sequence meant there was a lot of time when LMP2 cars were on pit road.

The no.7 Toyota was again the faster of the two TS050s, setting pole position and leading through the early hours before a mechanical failure again denied the team its dream result



If ever there was to be a more competitive class than LMP2 it is hard to imagine

There were a number of technical issues early on. One Signatech Alpine suffered a water leak as early as the first lap, while the the Racing for Holland ORECA also had a water leak. One of the United cars had an oil leak having run at the front of the pack, and Dragonspeed blamed engine supplier Gibson for its retirement from the race. However, Gibson responded that it potentially had only one problem with one engine, which was one of the Dragonspeed cars, but that it retired with a suspension issue before Gibson's engineers could get to the bottom of it.

Blocked fuel filters from contaminated fuel was thought to be an issue for some of the cars, but key to the race was the length of time the cars spent refuelling. United Autosport spent more than five minutes longer on pit road than the no.38 Jota entry, against which it battled for the class win (52m50s compared to 47m30s, although being held in pit lane under safety car conditions can affect the total pit time). Time lost in the pit had to be made up on track with clever use of safety cars and slow zones.

Ultimately, the battle was settled in favour of the United car, which recovered from a puncture that cut Paul di Resta's last stint in the car two laps short and forced the team to splash for fuel towards the end of the race. The car's responsibility fell to di Resta's co-driver Phil Hanson to fend off Anthony Davidson in the Jota entry and it was nip and tuck all the way. Jean-Eric Vergne suffered a suspension failure in the final hour which took them out of contention, and a crash for James Allen in the final hour cost Graff a podium, but also brought out the safety car.

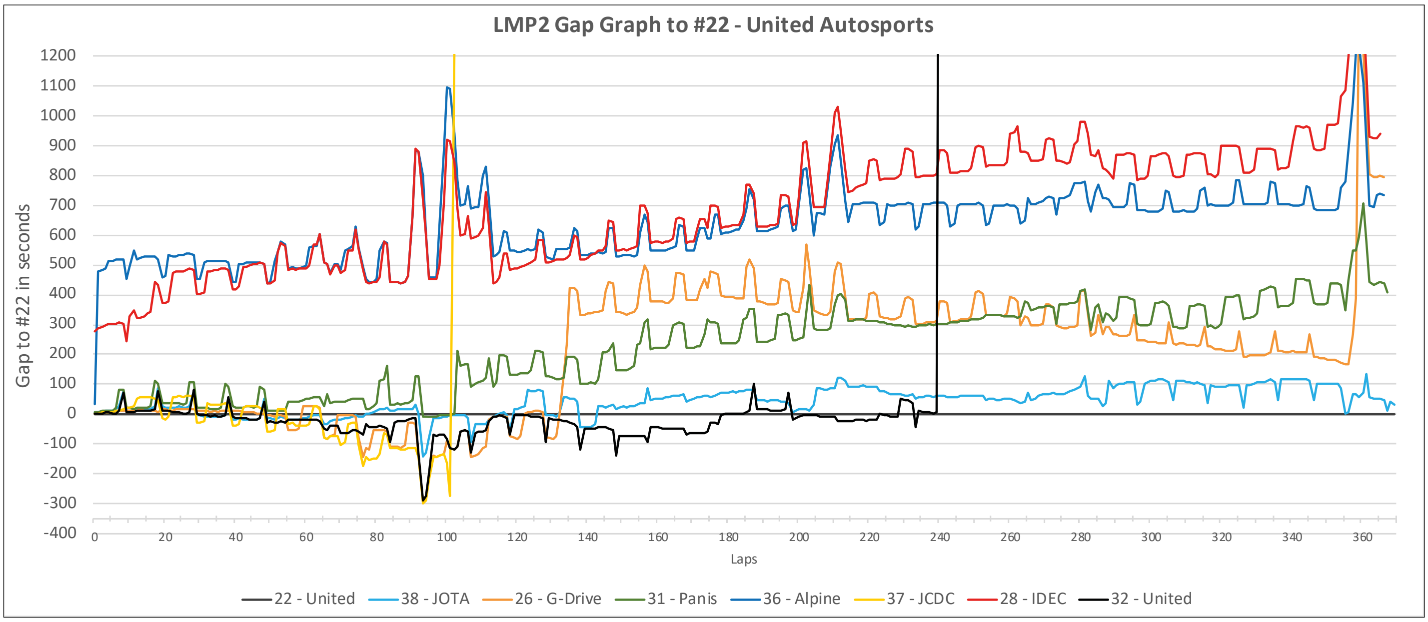
Hanson had taken over the United car with over an hour of the race remaining, after Di Resta's puncture curtailed his last stint to nine laps, rather than the expected 10. The Jota car pitted as scheduled and United believed they would not need an extra stop.

However, with 55 minutes remaining, an AM car crashed at Tertre Rouge, necessitating a slow zone be implemented there. This enabled some fuel saving at both Jota and United. No sooner had the mess been cleared up, though, there was another incident at the Porsche Curves, where the Graff LMP2 car crashed. For this, a full safety car was used, allowing more fuel saving still. Hanson managed to conserve enough to get 12 laps out of his stint, so when the SC was withdrawn after 15 minutes, Hanson continued for another four laps before pitting.

Next door at Jota, the team was hoping that Davidson would be able to save enough fuel to remove the need for a final stop altogether but, for some reason, the Briton only managed to get 11 laps out of his car. His subsequent pit stop was shorter than that of Hanson – one lap less of fuel required – but that only made five seconds difference. With the gap at the flag just over half a minute, it simply wasn't enough to make up the deficit.

While Hanson stood up to the pressure admirably in the final stint, earlier in the race, it was the pace of Di Resta and Felipe Albuquerque on Sunday morning that really made the difference. Da Costa, taking over the Jota car on Roberto Gonzalez's used tyres in a strategic gamble for the team, was slower than the United car, losing around 15s on the stint. Although Da Costa went quicker when he had new tyres, the second stint on the same set (he did a quadruple stint) was back in the 3m 33s bracket. Meanwhile Di Resta's stint just after 10am was the fastest P2 stint in the race, a good half-second quicker than Da Costa to put United in commanding position.

Rebellion took second place after a pretty much trouble-free run, but the team was still five laps behind the winning Toyota



United Autosport took the win in LMP2, despite losing four minutes on pit road. The margin of victory at the chequered flag was just over half a minute after a dramatic final hour that saw crashes and ultimate racecraft

TECH SPEC: ORECA LMP2 winner

Chassis: Carbon monocque with Zylon panels
Suspension: Double wishbone and torsion bar
Dampers: PKM
Brakes: Brembo discs, Brembo pads
Electric power steering: Kayaba
Tyres: Michelin
Wheels: OZ
Lights: Osram
Fuelling valve: Staubli, Krontec
Dimension: 4745 x 1895 x 1045mm
Weight: 930kg
Engine: Gibson 4.2-litre, normally-aspirated, 90-degree V8 GK428
Injectors: Cosworth
Oil: Motul
Clutch: Tilton
Gearbox: Xtrac

GTE

With just eight cars in the 'Pro' class this was not going to be one of the classic races, although 22 cars in the 'Am' category was interesting. The automated BoP system does not apply to Le Mans where human decisions take priority. Porsche subsequently felt it was on the receiving end of that issue and the rising averages certainly shows the new 911 RSR (introduced last year, but debuting at Le Mans) as the slowest of the GTE-Pro cars.

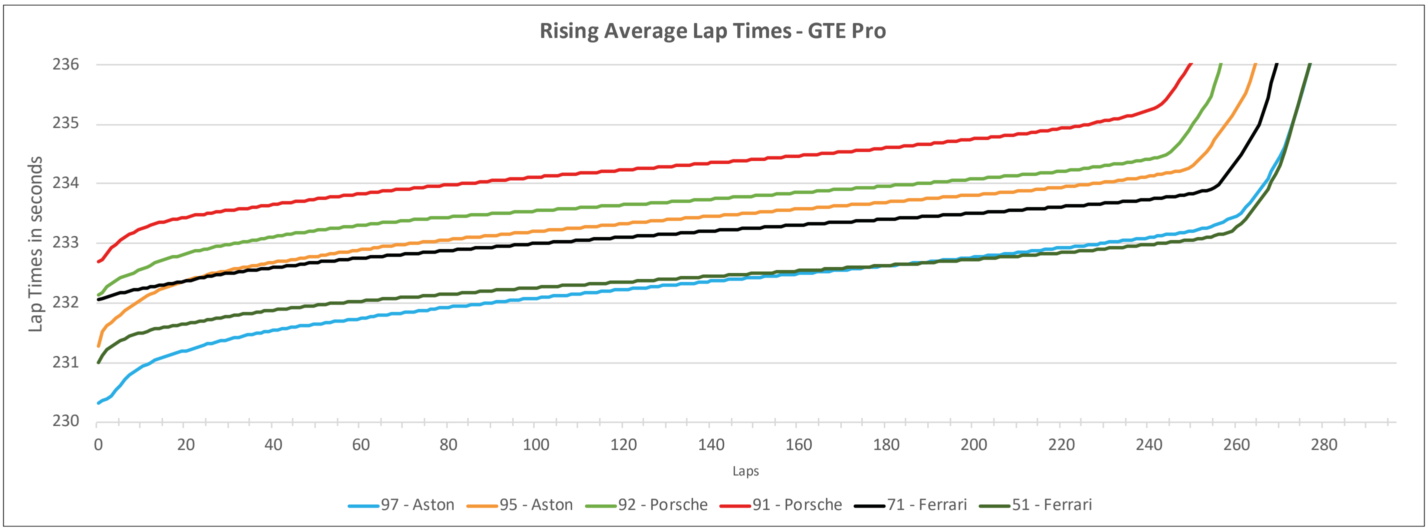
For much of the race, the no.97 Aston Martin had the speed advantage compared to the no.51 Ferrari that finished second, just 93 seconds behind after 24 hours of racing.

The difference between the two cars was that the Ferrari changed the front brakes during the race, the Aston Martin did not. Although the drivers did not necessarily focus

Porsche sat on pole position but, in the race, the other cars showed their true potential, leaving the Stuttgart marque behind

GTE Pro performance

Position	No.	Team	Car	Drivers	Laps	Best	Average	S1 - Best	S2 - Best	S3 - Best	Porsche - Best	Ford - Best	Top Speed
1	97	Aston Martin Racing	Aston Martin Vantage AMR	Martin/Lynn/Tincknell	346	03:50.321	03:51.740	35.702	88.012	105.910	17.726	6.537	306
2	51	AF Corse	Ferrari 488 GTE Evo	Calado/Peir Guidi/Serra	346	03:51.002	03:52.014	36.393	88.268	106.131	17.722	6.603	304
3	95	Aston Martin Racing	Aston Martin Vantage AMR	Sorensen/Thiim/Westbrook	343	03:51.277	03:52.864	36.426	88.462	106.246	17.801	6.716	303
4	71	AF Corse	Ferrari 488 GTE Evo	Rigon/Bird/Molina	340	03:52.059	03:52.730	36.434	88.522	106.422	18.025	6.673	305
5	82	Risi Competizione	Ferrari 488 GTE Evo	Pla/Bourdais/Gounon	339	03:51.408	03:52.667	36.310	88.292	106.280	18.004	6.630	306
6	91	Porsche GT Team	Porsche 911 RSR - 19	Lietz/Makowiecki/Bruni	335	03:52.695	03:53.809	36.099	89.165	106.514	17.656	6.591	299
7	92	Porsche GT Team	Porsche 911 RSR - 19	Christensen/Estre/Vanthoor	331	03:52.136	03:53.267	36.345	89.025	106.282	17.608	6.502	300
8	63	WeatherTech Racing	Ferrari 488 GTE Evo	MacNeil/Vilander/Segal	185	03:52.056	03:53.845	36.610	88.769	106.473	18.150	6.654	302



Partner team, TF Sport, won the GTE-Am category after also benefitting from improved rear tyre wear this year

TECH SPEC: Aston Martin winner GTE-Am

Chassis: Production-based aluminium
Suspension: Double wishbone and torsion bar
Dampers: Öhlins
Brakes: Alcon
Electric power steering: Kayaba
Tyres: Michelin
Wheels: TWS
Lights: Hella
Fuelling valve: Staubli
Weight: 1251kg
Engine: AMG Mercedes 4.0-litre, bi-turbo, 90-degree V8
Injectors: Cosworth
Turbos: Borg Warner
Oil: Total
Clutch: Alcon
Gearbox: Xtrac

TECH SPEC: Aston Martin GTE Pro winner

Chassis: Production-based aluminium
Suspension: Double wishbone and torsion bar
Dampers: Öhlins
Brakes: Alcon
Electric power steering: Kayaba
Tyres: Michelin
Wheels: TWS
Lights: Hella
Fuelling valve: Staubli
Weight: 1251kg
Engine: AMG Mercedes 4.0-litre, bi-turbo, 90-degree V8
Injectors: Cosworth
Turbos: Borg Warner
Oil: Total
Clutch: Alcon
Gearbox: Xtrac

Aston Martin spent three days perfecting its braking strategy in preparation for Le Mans, and it paid off as the team completed the race without changing the brakes to deliver the win for the Vantage

on saving the brakes from the start, they knew they would have to go the full distance without a change and so were careful.

According to Michelin, the key was their ability to look after the rear tyres, and even in the Am category that made a difference. What can be seen from the rising averages chart is the no.97 Aston was comfortably faster than the opposition, even with drivers paying close attention to brake wear.

Ferrari complained the BoP did not suit, but in race conditions its cars were fast and instead it was Porsche left embarrassed. The 911 sat on pole after the new hyperpole qualifying session, but blown fuses on the power steering systems put both cars out of contention. Even before that, though, they were well off the pace, and will no doubt want a review into their own performance and the organisation that regulates the BoP.

With only two cars from a planned four, it was perhaps a blessing their commitment to the race reduced on this performance.

Advance warning

Of the stewards decisions, number 108 caught the eye. AF Corse's Ferrari no.51 was investigated as the ignition advance did not match what was on the data sheet that forms part of the homologation of the cars and is supplied by Ferrari to the FIA.

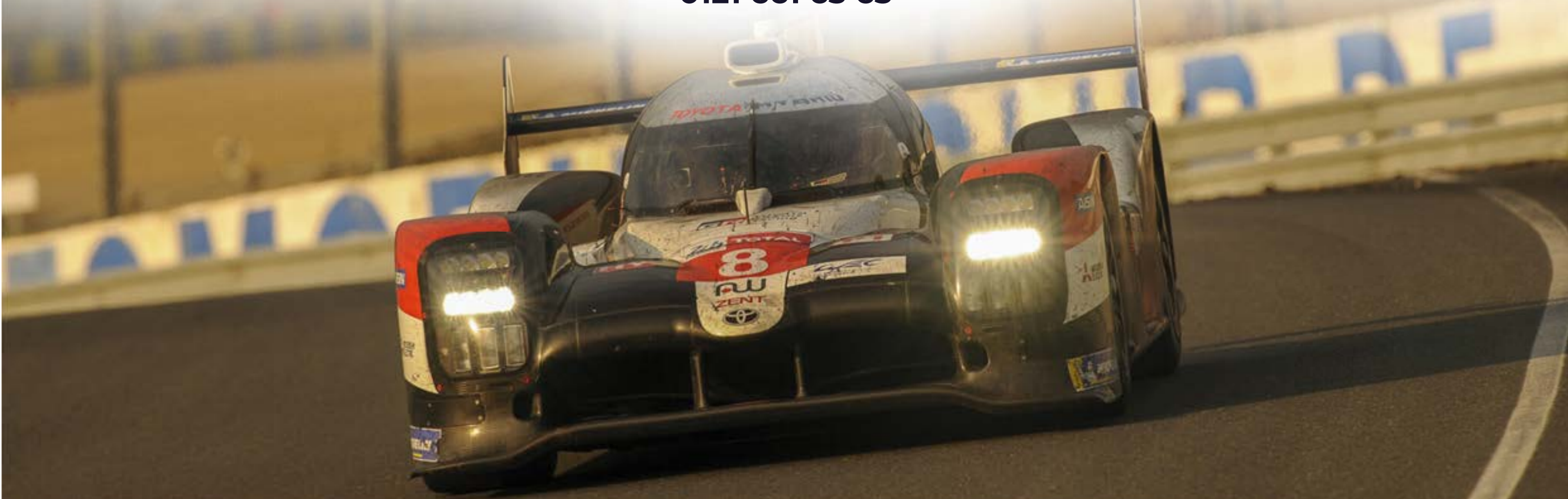
The sheet is used as part of the Balance of Performance process, and the FIA and ACO use it to help determine lambda and pBoost settings. AF Corse argued that the team has certain control strategies that set performance under different conditions to ensure reliability and that ignition advance is one of these, and is therefore not part of the performance balancing act.

No further action

The stewards were satisfied that, as the ignition advance is measured using the teams' own data and not an FIA sensor, there was no attempt to provide false information and so there should be no further action taken.

'The only question remaining to the Stewards is whether the ignition advance must strictly comply with the values set out in the Datasheet, which is gathered under specific conditions, not ambient conditions,' read the judgement.

'The Competitor argues that if their engine was tested under the conditions specified, the results would match the datasheet. There is no evidence to the contrary. Further, the Stewards are concerned that the data gathered does not use a controlled sensor. Engine parameters are a complex multi-variable system. It is clear to the Stewards that the datasheet must be accurate, and that pBoost and Lambda are fixed by the Balance of Performance. However, it is not clear that the other parameters of the engine can be expected to be constant.'



Power games

The top class in endurance racing will be called Hypercar and will incorporate both [LMDh and LMH] concepts

There was some flesh added to the bones of the LMDh regulations at Le Mans, but the picture is by no means final

By ANDREW COTTON

Friday's traditional ACO press conference at the 2020 edition of the 24 Hours of Le Mans saw the French organisation outline regulations for Le Mans Daytona h (LMDh) and reveal partners for the project, including Xtrac for the standard gearbox, Bosch for the hybrid motor and Williams Advanced Engineering (WAE) to provide the battery for the class that will be part of a global Prototype platform.

There are two ways of entering the top class that are already well documented. Either a manufacturer may build its own car, including chassis, suspension, brakes, engine and, crucially for some, the hybrid system. Or a second option will allow a manufacturer to buy an homologated chassis and fit its own engine and aero package (similar to the process allowed in the US by the IMSA organisation under its Daytona Prototype International (DPi) regulations) but fit a spec, low-powered hybrid system.

Global reach

The initial intention was that Le Mans Hybrid (LMH) cars run in the FIA's World Endurance Championship, while the LMDh concept was developed by American organisation IMSA. However, manufacturers and governing bodies want to balance the two concepts to allow them all to compete globally, increasing return on investment and controlling costs.

Therefore, rather than differentiate between the LMH regulations the FIA and the ACO created, and the LMDh regulations (the h has never been officially identified), the top class in endurance racing will be called Hypercar and will incorporate both concepts.

This goes alongside announcements earlier this year that the four chassis manufacturers from LMP2, namely ORECA, Dallara, Ligier and Multimatic, would also supply the chassis for the LMDh entry to the top class. These cars will be developed and homologated for five years, using the same process as the current DPi cars that currently race in IMSA's WeatherTech Sportscar series.

However, in order to protect its current competitors, IMSA has yet to commit to allowing LMH cars such as the Peugeot, Glickenhaus and Toyota to race in the States until the performance balancing process has been proven successful. That process is proving complicated, though, and the finer details have not yet been finalised.

Bespoke gearbox

While Peugeot dominated the LMH discussions, the first stage of the LMDh announcements in France was that Xtrac will provide a bespoke gearbox for the new category that will house the Bosch hybrid system. The British company already provides the gearbox to ORECA, Multimatic and Dallara LMP2 cars and was then chosen to supply all four chassis manufacturers in this second-generation rule set. The gearbox will be available mid-2021 for hybrid system testing, and cars are expected on track later that year in preparation for a race debut in 2022.

The P1359 gearbox developed for the class is a seven-speed transverse arrangement with an integrated motor-generator unit (MGU) driving into the gearbox through an optimised gear train. The integration of the hybrid system is a vital attribute of the LMDh specification and Xtrac has worked closely with the ACO, IMSA, Bosch and Williams Advanced Engineering to ensure the package, function and overall operation is optimised for cost, weight, performance, and reliability.

The LMDh spec hybrid system has a relatively modest output of 30kW, which is hardly intense when one considers the auxiliary exhaust gas MGU-H on the Porsche 919 Hybrid that raced at Le Mans from 2014-2017 achieved the same contribution in charging the battery in wide-open throttle.

WAE supplied Formula E's spec battery for the all-electric series' first four seasons, culminating in a system with a capacity of 28kW that produced a nominal race output of 180kW. It is also delivering the battery pack for the Extreme E series, which will have an output of 400kW, and will be the sole supplier of it in Extreme E's inaugural season.

Battery challenge

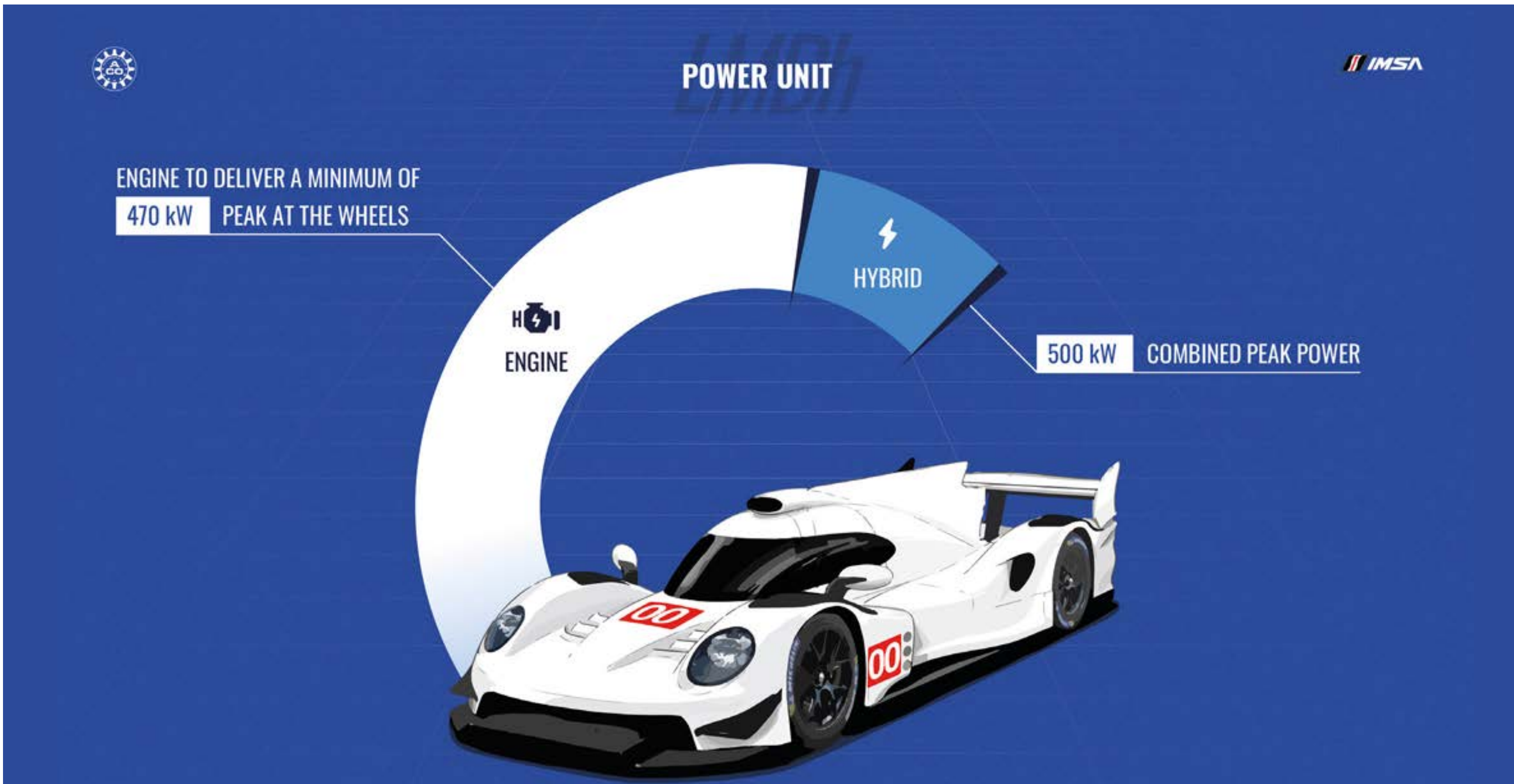
As for the LMDh spec battery system, Williams Advanced Engineering notes the challenge is very different from the spec systems it has provided in the past. Mainly because throughout the race at Le Mans, there is a substantial delta in ambient temperature, air pressure and humidity.

The battery and its ancillaries will be homologated, so the spec must perform well in each environment regardless, and understanding the working environment of the battery will play a significant role in the early part of its design phase.

Inside the battery, some elements are critically separated by an air gap that forms isolation between components, some of which carry current. Should a loss of isolation occur, new electrical pathways could form between parts, for which the amount of current and the length of time the current runs are not managed.

As such, the spec system for the LMDh category will probably be conservative in its volume to ensure there are no issues concerning isolation.

The WAE LMDh battery will likely use lithium-ion cell chemistry. The architecture of the electrode stack in the cell dictates the temperature range the cells can work efficiently in, so this will almost certainly differ from what WAE has used in its Formula E units as they operate in a narrower window.



Diagrammatic of what has been released so far in the way of LMDh specifications

To date, WAE has characterised many different cell chemistries and designed a unique pack construction to enable the desired cell behaviour for the various race series it supplies.

Regarding capacity and performance as far as rate of discharge, no information has been disclosed yet. However, as performance is primarily driven by how power is drawn from the cells within their operating temperature window, the mechanical installation will be critical, and it is not known yet whether that will be left to the teams or be in the hands of Williams.

The mechanical installation, which includes the cooling package, influences the output potential, but it's a very narrow road to performance development. As such, the primary influencer in motorsport battery performance is the software that governs how the energy is deployed and regenerated – something WAE will likely lock for the teams running in LMDh. 'The four appointed chassis suppliers, Dallara, Ligier, Multimatic and ORECA, provided invaluable feedback to Xtrac during the design of the transmission,' says Xtrac's chief executive, Adrian Moore. 'That ensured we met their requirements with a common transmission that will fit all chassis without modification. It was a vital goal to make sure we achieved the cost-effectiveness of this new class of racecar.'

The P1359 gearbox uses Xtrac's well-proven P1254 integrated valve actuator (IVA) gearchange system. It houses full form ground and Xtrem polished gears and shafts in a magnesium RZ5 casing, which is a structural part of the car taking all of the loads from the rear suspension and rear impact structure, rear wing and safety wheel tethers.

The gearbox has a maximum combined internal combustion engine (ICE) and MGU power capability of 585kW (785bhp), with the engine speed operating within the range of 6000 to 10,000rpm. As each chassis builder can homologate its own powertrain with specific gear ratios, the integrated MGU drives through a novel gear train that will be homologated for each engine. It ensures that no matter what the maximum engine revs, the MGU is matched to the engine speed, ensuring no one engine gains an advantage, parity being the ethos behind the new class.

The gearbox also includes a limited-slip plate differential with an externally gas charged pre-load and a semi-dry sump oil system. Integral to the gearbox is a 3.0-litre engine oil catch tank, which simplifies the powertrain installation. The whole package, including the MGU drive, but not including the MGU itself, weighs 78kg (172lb).

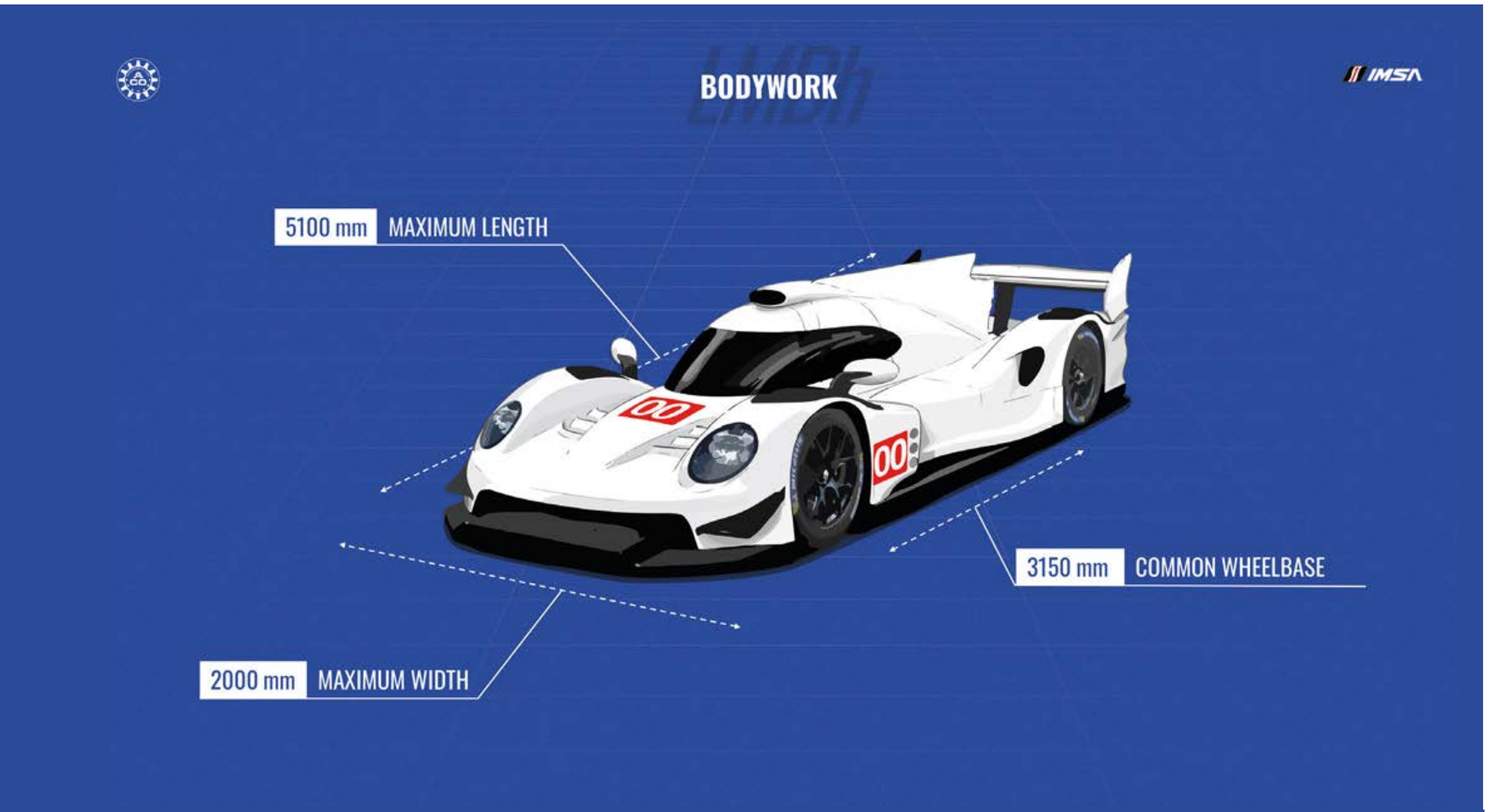
The P1359 gearbox, with its integrated hybrid system, is a critical new product for Xtrac. 'We see the transition to electrified propulsion systems both on the road and the track,' says Moore. 'We have compelling technology to help make motorsport even more relevant and exciting, which also influences the crucial evolution of the next generation of road cars.'

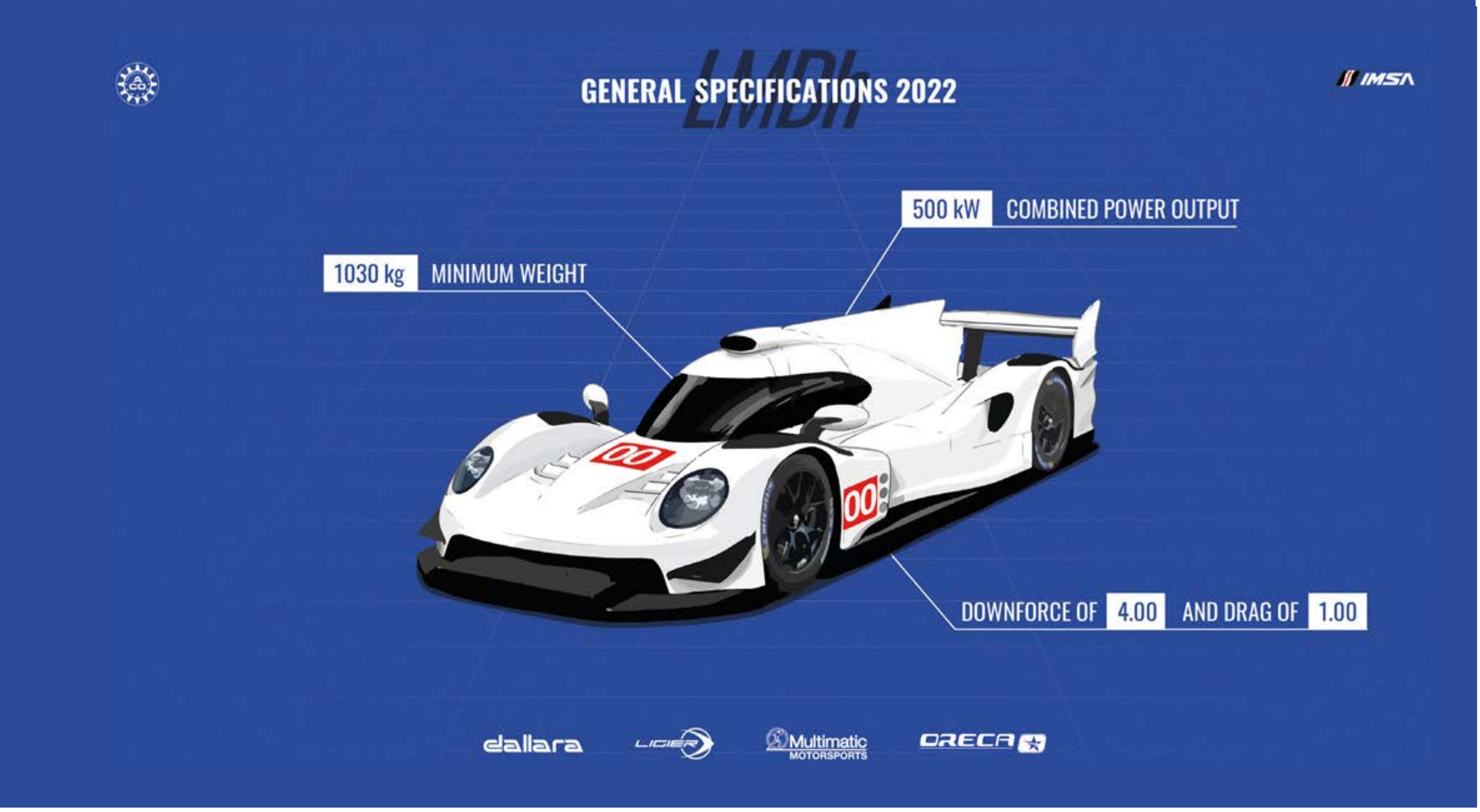
'We have compelling technology to help make motorsport even more relevant and exciting, which also influences the crucial evolution of the next generation of road cars'

Adrian Moore, chief executive at Xtrac

Complete package

The three companies, Bosch, Xtrac and Williams Advanced Engineering, worked together to present the organising bodies with a complete package. Bosch's responsibilities include the e-machine, inverter, vehicle control unit to the brake-by-wire system and other peripheral electronics, as well as key e-mobility hardware for the LMDh programme. Additionally, Bosch





provides an intelligent hybrid-power management software that controls the distribution of torque between the ICE, e-machine and brake-by-wire system, based on driver demand.

'With the hybrid system and our components, we are making an important contribution to the new racing category,' says Dr Klaus Böttcher, vice president, Bosch Motorsport. 'We are particularly proud that ACO and IMSA trust us with the responsibility of system integration in the future. For us, this is the next step in demonstrating our many years of expertise and competence in motorsport, both with our technology and with our system engineering expertise for a perfect interaction of all components.'

As the rule set fell under the watch of IMSA, it made the final decision on suppliers, in association with the ACO.

'Bosch and Williams have a lot of motorsport experience,' says Simon Hodgson, vice president competition, IMSA. 'This is a bespoke unit that has been designed and packaged with all the requirements associated with LMDh.

'Working with companies that are flexible and able to be constructive, it was apparent they would be partners. Xtrac was supplying to three of the constructors already.

Toyota demonstrated this roadgoing version of its hypercar at Le Mans. It will start testing in race trim in October this year and will be raced in 2021

'What we were trying to achieve with LMDh was a common gear case for efficiency of cost. The collaboration meant we could arrive at a common single class. We have been working with the partners for some time. It has been a very positive process.'

Focus on the LMDh regulations at Le Mans saw the basic outline of the car revealed, with weight set at 1030kg, a combined power output from ICE and hybrid at 500kW and a point on the lift / drag graph at which both LMDh and LMH cars will meet. Wheelbase is 3150mm by regulation, there is a maximum length of 5100mm and width of 2000mm. The car is priced at €1m (approx. $1,171,040), split between €300,000 (approx. $351,310) for the hybrid system and €700,000 (approx. $819,570) for the spine of the car.

Tyre concepts

Tyre sizes for the LMDh category were not identified and Michelin, the sole tyre supplier to the top category of both LMH and LMDh concepts, explained how the two concepts would have totally different requirements, and therefore their own bespoke tyre sizes.

'The Toyota tyres are the same size as today, but [on] the Glickenhaus you have a narrower front and wider rear,' says Matthieu Bonardel, head of Michelin's business line of the LMH tyres the company is developing. 'This is coming to life, they are not ready yet. Toyota are the first tyres ready and they will test soon, and we have enough data and confidence to be close to the target.

'Shifting to ByKolles and Glickenhaus, if they are performing on time, it is a case of how long it will take them to reach 95 per cent. Then, on our side we will use a front that is totally new, and a brand new rear, but we have never done a tyre that size. The first test will be interesting because if nothing works it could be the tyre or the car.

'Regarding LMDh, if the technical data shows it will be equivalent to ByKolles or Glickenhaus, they can use the similar tyre but, if they need a different type of tyre, we will be allowed to do it. Looking at the basic data, they cannot wait for the car to exist before we do the tyre, so they have chosen the same. Chassis makers can then design their cars.'

Parity of performance

Having different tyre sizes will be something that those sitting in the simulation working group have to overcome to balance the cars ahead of their introduction. They also have to find a way to balance power delivery. In order to achieve parity of power, limits were set at 500kW, with the LMH cars producing 200kW of power on the front axle through their hybrid system, while the LMDh concept cars will produce 470kW from their internal combustion engine, and a further 30kW from the spec hybrid system.

Power delivery for the LMDh cars will be constant, with the low-power system supporting the ICE throughout the acceleration phase, but the LMH cars will not have full hybrid power all the way round a lap.

> **'Working with companies that are flexible and able to be constructive, it was apparent they would be partners'**
> *Simon Hodgson, vice president competition, IMSA*

For them, the hybrid is only activated over 120km/h in the dry and power is likely to be limited due to a small energy storage. They therefore need to build an ICE engine capable of producing 500kW and convert the torque from back to front over the set speed limit.

The basic concept for the LMH cars is that they will be able to race at Le Mans at a lap time of between 3m25s and 3m30s in the first year. The LMDh cars should be able to do the same lap time, particularly as they race on the LMP2 platform that qualified at 3m24s at Le Mans in 2020. However, the LMDh fuel tank sizes are too small to compete on a level playing field with the LMH cars.

IMSA does not have a target lap time on any specific circuit, but do not want the LMDh cars to be too much quicker than the current DPi cars as they will have to be integrated at some point in the middle of the 2022 season.

'This is the next evolution, the next step, and will be around for a long time, bringing both stability and cost control'

Simon Hodgson, IMSA

The organisation says it will increase or reduce the hybrid power according to track when they start to see the LMDh cars.

'Technically, there is no reason why LMDh will not be in competition sometime in 2022,' says Hodgson. 'We are going to respect all entrants that are committed to us. LMDh is the next generation and that should bring something we don't have today. This is the next evolution, the next step, and will be around for a long time, bringing both stability and cost control.

'We are willing to extend homologation [of DPi] until LMDh is introduced. We haven't made any formal announcements about when LMDh will be introduced. The technical team has been focussed on producing what we have announced today.'

On Balance of Performance, there has been a strong dialogue between IMSA and the ACO so, although there is no formal agreement or BoP figures, both organisations are aware of the other's requirements.

Active simulation

'We don't want to make any statements yet, but every step of the way we haven't been working in a vacuum,' said Hodgson at Le Mans. 'We have taken into account the requirements of each championship, which is also driven by LMH and convergence. We have active simulation groups, including hybrid, so know the capability of our classes currently at those tracks and that is a baseline for trying to achieve parity of performance.

'Today, the step forward is the same tech specification so that LMDh can compete in two championships around the world. There is more news to come. Today we also want to speak to our manufacturer partners.'

Michelin was clear that the different tyre sizes, even between the older generation DPi cars and the new LMDh cars, could pose a problem for the Americans.

'Currently, DPi cars will have less grip,' says Bonardel. 'The LMDh cars will last longer [on fuel and tyre wear]. There will be more rubber, first, and for DPi we took technology that is close to LMP2. LMP2 is not a confidential tyre, so we don't want to use the best technology that we have because these are tyres we disclose, [but] I think the tyres for LMDh will be faster and more durable. We have to bear in mind that the LMDh car will be heavier as well. The DPi is better than LMP2 [in terms of performance]. How they manage the transition from DPi to LMDh is up to IMSA.'

The announcement of the new regulations certainly had a positive effect on the paddock at Le Mans, but there were also concerns voiced surrounding costs. Although the two series will put the cars into a performance window that allows them to be balanced, they have to perform to the same high level in all conditions to be competitive. Clearly, there is still a great deal of work to do before this rule set is final, and before IMSA throws open the door to LMH to race in the US. However, the first couple of tentative steps have now been taken.

It's the end of the road for DPi in 2022 as LMDh is on its way and is expected to arrive mid-season

Rubber necking

Michelin is sole tyre supplier for LMDh and LMH and plans to use the opportunity to introduce new technology into its range.

'Today we have the technology to put a sealant in the tyre, which makes it resistant to puncture,' explains Michelin's Matthieu Bonardel. 'You put a gel in the tyre and that fills the puncture and keeps the pressure. We have that technology, but when you try to put 200g more weight into each tyre, so almost 1kg, it could cost half a tenth, and then the driver says it is slower. What is the risk of the puncture? They then don't want it. That started with Audi. We told them we could get rid of punctures if you guys want it, and they said no, they want the fastest tyre. They take the risk because they had three cars and it is less likely to happen to all three.

'Now we can decide what we want, and so we want to try that. It is on road tyres now, so why not on race tyres? It is a good place to try.

What I expect is that the next two generation of tyres will not have a problem warming up

Matthieu Bonardel, head of Michelin LMH product line

'Another thing I really want is to get rid of tyre warmers. What I expect is that the next two generation of tyres will not have a problem warming up. The current tyre design is for tyre warmer conditions, and if you don't do that you lose lap time. However, designing a tyre to warm up in cold conditions is going to prevent using technology that makes the tyre very grippy when it is warm. It is not as good, and the tyre spends more time warm than cold. So, it is a trade-off you don't want to do if you face competition.

'[The tyres] will be a second or two slower. But if I put some research into that, and I decide it is what I want to do, we can reduce the trade-off over the next four years to perhaps zero.

'The second year is still a big bet because of LMP2. If they overtake the Hypercars [on warm tyres], the championship looks bad. The data says even today with current tyres, with weight, horsepower and what we have in mind, at Le Mans it should be okay. But we have to be careful on slow speed tracks not to reduce performance too much or the LMP2 will be faster.

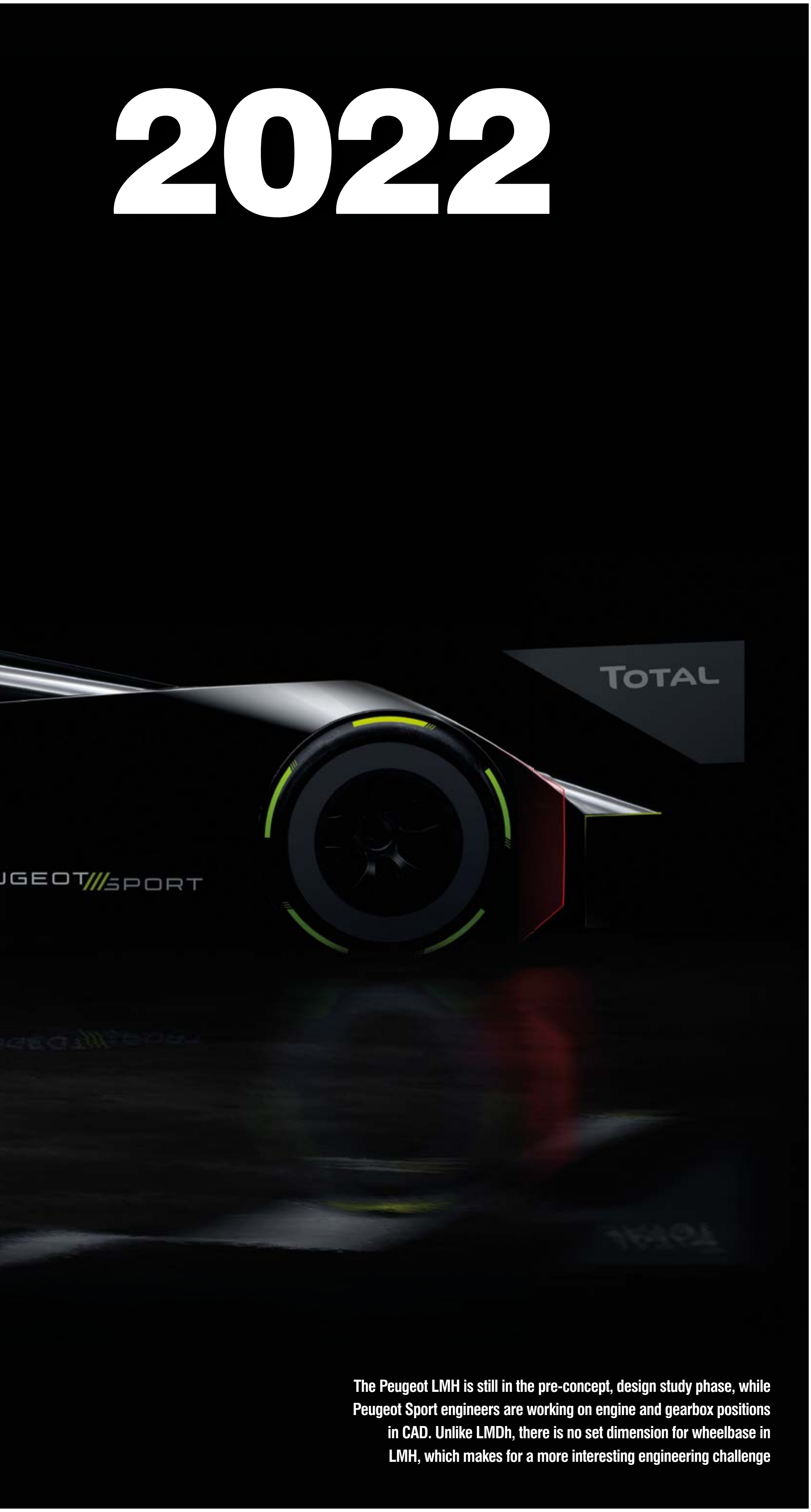
'Today, the ACO wants Goodyear to provide tyres that are slower [for the LMP2 class], but why would they do that? The only way to do that is if the ACO says to get rid of tyre warmers. If nobody has tyre warmers and everyone accepts losing one or two seconds per lap, we could stop using them. We have to consider where we are in 10 years. In cars, it deserves a try.'

Stardate

How Peugeot Sport is approaching its LMH programme

By STEWART MITCHELL

2022



The Peugeot LMH is still in the pre-concept, design study phase, while Peugeot Sport engineers are working on engine and gearbox positions in CAD. Unlike LMDh, there is no set dimension for wheelbase in LMH, which makes for a more interesting engineering challenge

Following the ACO and IMSA firming up much of the regulations for the newly introduced LMDh class, along with Le Mans Hypercar (LMH) at Le Mans 2020, Peugeot Sport and its technical partner, Total, confirmed that it will be entering the LMH class in 2022, a year earlier than expected. The decision to enter the LMH category was dictated primarily by the aerodynamic freedom allowed in this class, at least when compared with LMDh regulations.

'With LMDh based on current LMP2 architecture, this makes it impossible to incorporate the aesthetic detail of the Peugeot Sport brand,' comments Peugeot brand CEO, Jean-Philippe Imparato. 'After launching the various phases of studies for general [LMH] structure, aerodynamic concept and the choice of engine architecture, comes the final decision of the electrical framework, and then that of the conception of the hybrid traction chain. All of the Peugeot Sport technical departments are involved in these development phases.'

Provided a specific overall aerodynamic efficiency is not exceeded, teams developing cars for the LMH category have a good deal of freedom in the 5m long and 2m wide vehicle.

Technical director at Peugeot Sport, Olivier Jansonnie, continues: 'To date, we have confirmed part of the aerodynamic concept, the engine framework and have chosen the functionality of the hybrid system and its fundamental design. We still have several steps left before we make our debut in endurance in 2022 – in studies, the production of prototypes and, finally, affirmation on the bench and the track.

'We are not in the building stage yet, we are in the pre-concept phase, starting the design study, which is laying out in CAD the engine, gearbox and wheelbase setting. LMDh regulations have set wheelbase dimensions, [but LMH regulations] have maximum and minimum overhangs and overall dimensions, and you still have some adjustments on the wheelbase.'

Engine choice

As per LMH regulations, the Peugeot Sport car will be four-wheel drive, outputting a total of 500kW with a front axle-mounted electric motor with a peak output of 200kW, together with a centrally-mounted, internal combustion engine driving the rear wheels.

Engine design for LMH is relatively free, the rulebook only prescribing that petrol four-stroke engines are permitted, with several different levels of technical scope depending on the constructor's choice. Manufacturers are free to develop a bespoke engine or use one based on an 'engine of the make' series production power unit, mounted in a car model of the same group and produced in a minimum quantity.

For bespoke engines, there are a number of rules designed to prevent escalating costs at the R&D stage. Amongst them, only four reciprocating poppet valves with axial displacement are allowed; no more than two inlet and two exhaust valves per cylinder; the sealing interface between the moving valve component and the stationary engine component having to be circular; and electromagnetic and hydraulic valve actuation systems are forbidden.

Should a manufacturer choose the 'engine of the make' option, the regulations open up somewhat, including allowing the use of variable valve geometry devices, provided the system remains as designed for the original engine. The only drawback is in the minimum volume requirement, which states at least 25 identical engines homologated for a series production road car must have been produced by the end of the year of the first season the engine is competing in, and 100 by the end of the second year.

With very few other restrictions, this brings the potential for using roadgoing 'hypercar' engines into the fray, which can be far more sophisticated than those prescribed by the bespoke race engine category.

Energy choice

It is a similar story with the ERS and energy store, though the deployment regulations restrict the design and development teams from going crazy in this area. For the LMH cars, the electrical DC power of the MGU-K must not exceed 200kW and, except for the pit lane, the MGU-K can only apply positive torque to the front wheels if the speed of the car is 120kph or higher when fitted with dry weather slick tyres, or over 140kph on wets.

As with the internal combustion engines, the choice of bespoke MGU-K or series production-based 'MGU-K of the make' is allowed, with different prescriptions for each.

For teams opting to design and manufacture a bespoke system for the LMH category, the unit must be a single MGU-K with rotational speed no higher than 25,000rpm, a laminate thickness no less than 0.1mm and it must be solely and permanently mechanically linked to a fixed ratio drive with a homologated ramp on the front axle.

The 'MGU-K of the make' option has no such upper rpm, laminate thickness or number of drive units limits, but the same homologation rules as engines apply.

Jansonnie notes some nuances in the LMH powertrain concept and power delivery: 'You can't store enough energy in the battery to deliver the [full 200kW] of energy for the whole lap, you must be selective and deploy electric power when most suitable. You need to rely on the engine to provide [the full permission of] 500kW at the back, so need to design an engine to supply that power.'

Peugeot's Endurance Racing Record

2011 (Peugeot 908 HDi FAP)
1st, Intercontinental Le Mans Cup

2010 (Peugeot 908 HDi FAP)
1st, Intercontinental Le Mans Cup

2009 (Peugeot 908 HDi FAP)
1st and 2nd, Le Mans 24 Hours

2007 (Peugeot 908 HDi FAP)
1st, Le Mans Series

1993 (Peugeot 905)
1st, 2nd and 3rd, Le Mans 24 Hours

1992 (Peugeot 905)
1st, Sportscar World Championship
1st, Le Mans 24 Hours

When asked whether the turbocharged, 1.6-litre, inline, four-cylinder engine Peugeot's partner company, Citroën, used in the WRC up until the end of the 2019 season would be appropriate for the LMH programme, Jansonnie responded, 'With the need to deliver 500kW, we need something more significant than that, and Le Mans is a very different discipline. There will be some carry over of knowledge, but it is a new engine, and all I can tell you at this stage is we are doing the engine ourselves, in-house.'

Total involvement

Total is a multi-energy company, incorporating battery manufacturer SAFT, that answers mobility and energy demands in many sectors, and the Le Mans Hypercar project is allowing the company to study new battery solutions alongside Peugeot.

According to Philippe Montanteme, Total strategy / marketing and research director; 'The Le Mans Hypercar project provides us with possibilities for joint development on the entire energy system of the car, on the efficiency of our fuels – for all competitors, as the exclusive supplier – and for the lube, specifically designed for hybrid vehicles.'

Until 2023, Total is the official fuel supplier for the FIA World Endurance Championship (WEC), which includes the 24 Hours of Le Mans. Total supplies an E20 fuel, 20 per cent ethanol in petrol, which offers a higher octane rating (Research Octane Number (RON) 105), leading to improved anti-knock properties, and a higher oxygen content when compared with regular petrol. Those reflect the current concerns of manufacturers and motorists of consuming less fuel, and reducing their environmental footprint.

This high-octane WEC fuel also makes it possible to optimise both compression ratios and ignition settings for turbocharged engines, improving their thermal efficiency and increasing longevity.

Total also produces a unique endurance racing lubricant for the engines and gearboxes running in Le Mans conditions, where a 70 per cent wide open throttle load situation is commonplace. As well as being able to cope in these extreme conditions, the lubricant must be capable of working in an unusually wide heat range as the race goes through night and day. At the high ambient temperatures experienced during the day, the lubricant has more difficulty cooling down, so the exchange between air and oil needs to be very specifically tailored to this environment.

It uses a specific base oil stock and the right viscosity must be chosen to ensure the oil thickness is never broken through to the bearings throughout the engine.

Total has gone to great lengths to reduce the viscosity, as adding a thicker oil film to the engine might reduce internal friction, but causes challenges in evacuating all of the oil galleries that feed the mechanical parts. Also, if the oil is too thick, the radiators are not able to cool it down quickly enough because the heat exchange properties drop proportionally with fluid density.

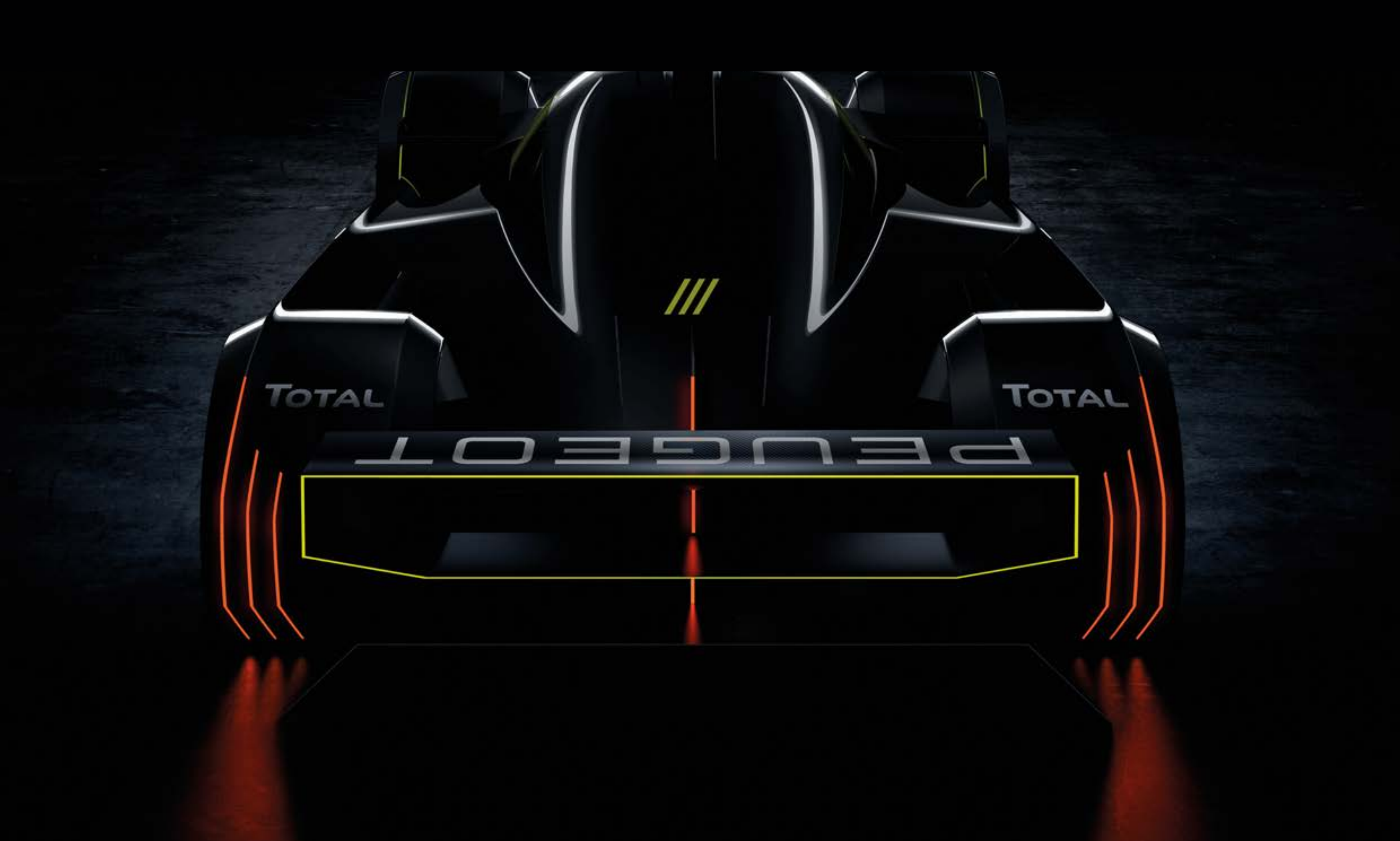
The trade off with using a highly viscous oil is oil pressure must be increased to ensure the required film thickness on components is maintained, though this technique is usual for endurance racing engine applications.

'It is a new engine, and all I can tell you at this stage is we are doing the engine ourselves, in-house'

Olivier Jansonnie,technical director at Peugeot Sport

‘To date, we have confirmed part of the aerodynamic concept, the engine framework and have chosen the functionality of the hybrid system and its fundamental design’

Olivier Jansonnie



Engine oil temperature at Le Mans can reach as high as 150degC, at which point some base oils in engine lubricants begin to break down. To combat this, Total developed a fully synthetic oil with an ester compound and mPAO base fluid that has better heat exchange capabilities than hydrocarbon-base fluids and allows for the use of an additive package to reduce friction. The polymers in the base fluid do not have high heat exchange characteristics, but they help on the high-pressure condition with no effect on the heat release of the fluid.

Le Mans also has an issue with oil contamination. Even with the robust air filter systems used on today's race engines, some debris makes its way through the combustion chamber and into the lubricant. As a result, Total adds a polymer to the oil that surrounds and helps contain these unwelcome particles, preventing them from adhering to any metal parts within the engine.

Total and Peugeot have carried out significant testing to ensure the minimum mileage of any contaminated oil can withstand the harshest stint conditions at Le Mans. Oil analysis is allowed during the race itself, and is crucial to determining wear inside the engine during the race and so is widely used by endurance racing teams.

The oil capacity of Le Mans racing engines is high, often around 50 per cent more than a road car platform with the same configuration. This high capacity also helps lower thermal loading and stress on each molecule of oil as the loads are spread across much more fluid.

A question of Balance

LMH incorporates Balance of Performance (BoP) between manufacturers in the class, and with the LMDh class. As to whether the LMH cars will have better acceleration due to their four-wheel driveline, Jansonnie elaborates: 'BoP sets limits, but also allows room for many technical possibilities in our development, specifically on the general shape of the power delivery.

'The concept between us [LMH] and LMDh is different, firstly because LMDh is two-wheel drive and we are four-wheel drive by regulation. Secondly, we have to use an engine that can deliver 500kW. We must therefore accept convergence of performance between LMDh and LMH because, at the end of the day, it will be profitable for everyone. And BoP is supposed to balance everything anyway, so there will not be a big difference between each of the cars.

'They have to get the BoP right, though, and IMSA has to allow LMH cars to run in the US. They haven't done that yet, but we expect that to come out of the simulation working group, which we are in the middle of the process at the moment.

'The simulation working group is currently working on defining the energy consumption per lap, giving the cars the same stint duration and aero homologation. These definitions should not be something intrusive into the design of any cars at this stage as we all still have flexibility.

'BoP will make sure everyone can be in the window, that is the game of the BoP. We know that the FIA will do 1:1 scale wind tunnel testing during the homologation process, so we will be doing the same.'

Development schedule

One challenge facing Peugeot is tyres. Michelin is sole supplier to the category, and has already developed the Toyota family of tyres as its hypercar starts testing this month (October). 'We have no baseline,' admits Jansonnie. 'People already involved in LMP1 have more experience of the current tyres, and we are quite comfortable in looking at solutions by simulation, but putting a number on the lap time? Right now, we are not going to be able to do that.

'We have the same concept as Toyota, [and Michelin has] one family optimised for four-wheel drive applications. To balance other tyre sizes, and with those running rear-wheel drive, will be tricky to set up.'

To compensate for this, Peugeot Sport has built up a development schedule that takes them to 2021 for the car's first test. Many of the team personnel in the LMH programme are from the 908 project, so know all too well how tough it is to design, build, develop and bring a car to the track that is reliable and performs well enough to win at Le Mans.

'BoP sets limits, but also allows room for many technical possibilities in our development, specifically on the general shape of the power delivery'

Olivier Jansonnie

'We are not underestimating the task,' says Jansonnie. 'We have a high opinion of the opposition, and we want to come to Le Mans and be ready. The new LMH will be a homologated car, and you don't want to homologate the car too early in the development phase and freeze everything in the car before you can improve it.

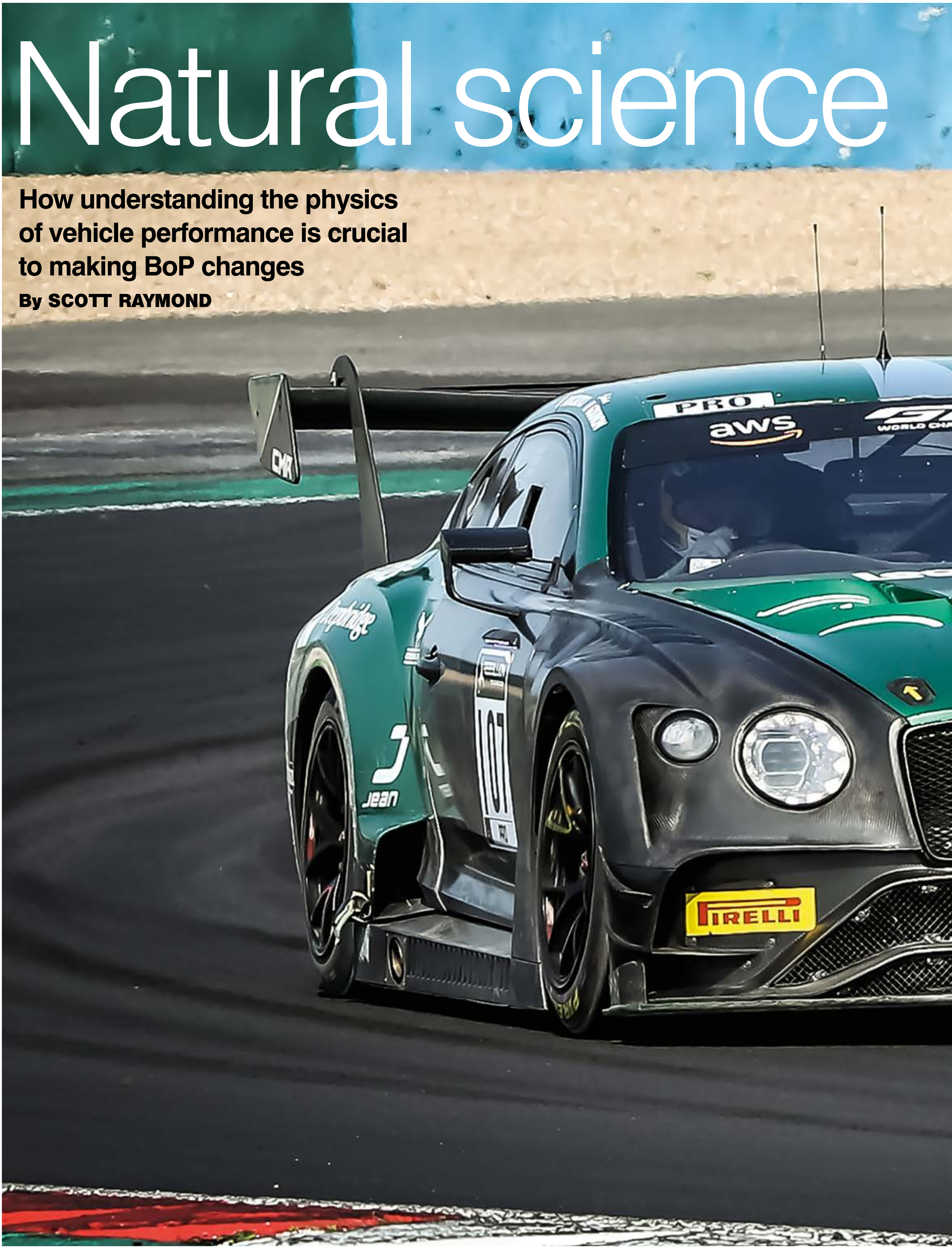
'The homologation process will be long, and you have some milestones of when to disclose information to the FIA first, and then finally give more details. The beginning of the process doesn't matter, it is when you come to an end, and the FIA freezes your car, that is when it is crucial. We will race in 2022, and we will be ready then.'

Peugeot's previous Le Mans effort was the 908, which developed into the 908 Hybrid4 for 2012, but the programme stalled

Natural science

How understanding the physics of vehicle performance is crucial to making BoP changes

By SCOTT RAYMOND



SRO / Patrick Hecq Photography

BoP variables typically include mass, total power output, minimum ride height, aerodynamic elements and tyres. All of these can be related back to physics

When attempting to balance vehicles, what we are really doing is manipulating the ability of a vehicle to generate longitudinal and lateral forces

In previous issues of *Racecar Engineering* (V29N12 and V30N3) we have discussed several key concepts regarding Balance of Performance (BoP). First, it was identified that BoP decisions should not be politically based, and we should not forget about first principles of engineering when analysing the performance of vehicles. Second, we discussed the myriad things that make BoP decision making difficult, with the trickiest issue of all being sandbagging, or performance management (see *RE* V30N7).

With the knowledge of this background information, we can move on to discussing the act of making changes to the Balance of Performance for a group of vehicles. But first, again keeping first principles in mind, we need to ensure we understand the physics problem we are dealing with. Once we understand this, we will move on to look at what options are available for making changes to BoP tables, and how these influence vehicle performance.

Equations of motion

At the very highest level, the performance of a vehicle around any circuit is subject to Newton's Second Law, F = ma, coupled with some equations of motion. The description that follows is basically how vehicle dynamics simulations work.

Starting with the equations of motion, the motion of a vehicle around a circuit is dynamic, where the vehicle is travelling through three-dimensional space over time. If we break this motion through space into smaller and smaller time intervals, we can start to think about the state of the vehicle for each of those time intervals as having a set of initial conditions, and a set of final conditions. When the time intervals are reasonably small, it is possible to approximate the change in the vehicle state from initial to final condition as a constant acceleration problem. Using this approximation, we can apply the SUVAT equations of motion from physics to get from the initial vehicle state to the final vehicle state. SUVAT is an acronym where s = displacement, u = initial velocity, v = final velocity, a = acceleration, and t = time.

For now, we will assume we already know the vehicle's acceleration so, if we also know the initial velocity and time step, we can apply the second SUVAT equation to calculate the displacement of the vehicle during the time step ie $s = ut + \frac{1}{2}at^2$. In addition, we can apply the first SUVAT equation, $v = u + at$, to calculate the final velocity of the vehicle at the end of the time step. For the following time step, the initial velocity is the final velocity from the previous time step, and from there we can proceed to evaluate each time step sequentially. However, we cannot accurately do this until we know what the vehicle's acceleration is for each time step.

SRO / Patrick Hecq Photography

Using the SUVAT equations of motion from physics, all vehicle movement on a racetrack can be broken down into a set of time intervals with initial and final conditions

At this point we need to take Newton's Second Law into consideration. From the above application of the equations of motion, we can see that the velocity of a vehicle at any point around a circuit is governed by the vehicle's ability to accelerate. Therefore, it is best to think of Newton's Second Law expressed in terms of acceleration ie a = F/m. We need to think of this equation as the acceleration equalling the sum of all forces (total force) divided by the mass. These total forces include those available for propulsion, and those forces resisting propulsion.

For example, a block sitting on an incline will have two forces acting on it: a gravitational force and a frictional force. The component of the gravitational force that is parallel to the surface of the incline will act to pull the block down the incline, but the friction force between the block and the surface of the incline will resist this component of the gravitational force. If the gravitational force component is smaller than the friction force, the block will not move. It is only once the gravitational force component is greater than the friction force that the block will begin to accelerate down the ramp. So, acceleration cannot happen until the total force – the sum of propulsive forces minus the sum of resistive forces – is great enough. Hang on to this concept as we start applying it to a vehicle.

The idea of breaking forces into directional components definitely applies to the motion of vehicles. In fact, we cannot work with the SUVAT equations or Newton's Second Law *until* we break the forces acting on a vehicle into two components. We need to break the equation a = F/m into its respective longitudinal and lateral components yielding two equations to work with: longitudinal acceleration $a_x = F_x/m$, and lateral acceleration $a_y = F_y/m$. Considering the concept of total forces, the longitudinal acceleration is equal to the total vector sum of all longitudinal forces divided by the

The idea of breaking forces into directional components definitely applies to the motion of vehicles

If the inertial force exceeds the available tyre force, the vehicle leaves the curved path, which often ends spectacularly poorly for the occupants of the vehicle

vehicle mass, and the lateral acceleration is equal to the total vector sum of all lateral forces divided by the vehicle mass.

Longitudinal acceleration

The longitudinal acceleration, a_x, is the acceleration we feed into the SUVAT equations and is the only acceleration we need to consider when looking at a straight-line acceleration problem. We know the longitudinal acceleration is the sum of longitudinal forces divided by the vehicle mass. The longitudinal propulsive force for a vehicle comes from the vehicle's power unit. For a typical internal combustion engine, the engine's output torque is fed through a drivetrain (clutch, driveshaft, gearbox, differential, axles, hubs and wheels) to the vehicle's tyres. This torque acting through the tyres results in a force parallel to the road that attempts to drive the vehicle forwards. This is not the only force we need to consider here, though. Just as there was a frictional force resisting motion of a block on an incline, there are several forces that resist the propulsive force from the engine and tyres. These resistive forces include frictional losses from within the drivetrain, rolling resistance from the interaction of the tyres with the road surface, aerodynamic drag and any applied braking forces.

Lateral acceleration

The lateral acceleration component, a_y, does not directly impact the SUVAT equations, but it does indirectly impact them in that the longitudinal acceleration of a vehicle is limited by the total possible combined acceleration ie the vector sum of the lateral and longitudinal acceleration. Before we consider combined acceleration or combined forces, first think about a pure cornering situation around a constant radius corner. In this scenario, the vehicle corners at a constant velocity that is related to the lateral acceleration through the equation $a_y = v^2 / R$, where v is the constant velocity around the corner, and R is the radius of the corner. We are still dealing with a situation with lateral acceleration resulting from the total lateral force divided by the vehicle mass, and we still have propulsive and resistive forces in lateral direction.

The propulsive force, or the force that is driving or pushing the vehicle towards the instantaneous centre of curvature, comes from the ability of the vehicle's tyres to generate a lateral force between the tyre and road. This is essentially a frictional force that increases as the vertical load on the tyres increases. The resistive force comes from the inertia of the vehicle. Like all bodies in motion, the vehicle does not want to turn because it wants to keep travelling along happily in a straight line. This inertial force wants to push the vehicle back to travelling straight, so it pushes it away from the instantaneous centre of curvature. When the lateral force from the tyres equals the lateral force from inertia, the vehicle is balanced and can travel around the curved path.

If the inertial force exceeds the available tyre force, the vehicle leaves the curved path, which often ends spectacularly poorly for the occupants of the vehicle. When the inertial force is less than the lateral force potential of the tyres, the vehicle can speed up and travel around the corner faster, or take a smaller radius line around the corner.

Combined acceleration

On the topic of combined forces, where you have both lateral and longitudinal vehicle accelerations, or lateral and longitudinal tyre forces, we are really talking about the ability of a tyre to generate combined force. A tyre is just a big elastic, and an elastic generates force when it is stretched. Unfortunately, an elastic can only stretch so far before it fails. Longitudinal forces stretch the tyre parallel to the direction of travel, while lateral forces stretch the tyre perpendicular to the direction of travel. The total stretch, or total force the tyre can generate, is the vector sum of the lateral and longitudinal components.

This concept is demonstrated through a tyre's friction ellipse, where the outer limits of the ellipse define how much combined stretch / force the tyre can handle. When the combined force exceeds this boundary limit, the tyre either loses grip by snapping back to a less strenuous amount of stretch, or fails where the rubber in the contact patch literally falls apart. The point here is that for a given amount of lateral force, a tyre can only generate a fraction of the maximum possible longitudinal force.

Even when BoP is done successfully, drivers and teams still have to manage tyre wear throughout a race and performance changes according to conditions, set-up, driving style and pre-race preparation

Returning to the SUVAT equations, we can now see how lateral force and acceleration impact the available longitudinal force a tyre can generate, which in turn limits the longitudinal acceleration available to calculate the distance travelled and final velocity of each time step.

Why have we spent this much space discussing the physics of vehicle performance? How is this related to Balance of Performance? Well, Balance of Performance is simply a physics problem. When attempting to balance vehicles, what we are really doing is manipulating the ability of a vehicle to generate longitudinal and lateral forces, which in turn determines how the vehicle accelerates longitudinally and laterally. I really want to emphasise this point strongly because, if we think of BoP as a physics problem, we can begin to have a much better understanding of how changes to vehicle parameters will influence the overall performance of a vehicle. And the better we understand the physics, the better we will be at making changes!

Options for changes

With the physics behind us, we can now look at what parameters we can change, and think about how these parameters influence the performance of a vehicle. The physics discussion helps us link parameter changes to the primary modes of operation of a vehicle around a circuit, travelling in a straight line and cornering.

Different racing series have different options available to adjust performance of vehicles, but the general BoP variables typically include mass, total power output, minimum ride height, aerodynamic elements, fuel capacity and, to some extent, tyres.

Mass

As implied by Newton's Second Law, the mass of a vehicle directly, and inversely, impacts the ability of a vehicle to take advantage of the propulsive forces to accelerate. Whether we are talking about longitudinal or lateral accelerations, any increase in mass will reduce the acceleration capacity in those directions, while any reduction in mass will improve the acceleration capacity of a vehicle.

Because of the direct impact of mass on longitudinal and lateral accelerations, we can increase a vehicle's mass to slow it down or reduce a vehicle's mass to speed it up. A good rule of thumb is that a 10kg increase or decrease in mass will result in a 0.15 per cent increase or decrease in lap time, respectively. So, on a 100-second lap, 10kg will have a 0.15 second impact.

Before we leave the topic of mass, think about how mass then influences the lap time of a vehicle as far as fuel is consumed. A vehicle with a 100l fuel tank will be carrying approximately 72kg of fuel at the beginning of a stint. By the end of the stint, and assuming no tyre degradation, this vehicle should be approximately 1.08 per cent faster (again, on a 100-second lap).

The physics discussion helps us link parameter changes to the primary modes of operation of a vehicle around a circuit

Total power output

As we discussed already, a vehicle's power unit is responsible for generating its longitudinal propulsive force. This force, when all the resistive forces are overcome, is what drives the vehicle forwards though space, and defines how quickly the vehicle can accelerate longitudinally. A higher capacity for longitudinal acceleration leads to a reduction in lap time, while less acceleration capacity yields a slower lap time.

There are many configurations of power unit encountered in racing, normally aspirated internal combustion engines, turbo / supercharged internal combustion engines, hybrid engines and fully electric motors. I am going to focus here on normally aspirated and turbocharged engines.

With normally aspirated engines, the total power output is primarily controlled by inlet air restrictors with a specified minimum diameter. These control how much air flows into the engine, which in turn determines

how much air is available to mix with fuel for combustion. Increasing the minimum diameter of a restrictor increases the volume of air that flows into each combustion chamber, which means a higher volume of fuel can be mixed with the air, and a bigger explosion can be created. So, a larger restrictor diameter equals more power, while a smaller one equals less power.

Engine restrictors come in two varieties, sonic and non-sonic. Sonic restrictors have a continuously curved profile along the length of the restrictor – much like the outlet of a trumpet – where the minimum diameter is found somewhere along the curved profile. Non-sonic restrictors typically have a conical inlet and outlet with straight walls and a flat cylindrical central section where the minimum diameter is found. A small radius is applied where the straight walls meet the flat cylinder, and the length of the cylinder is prescribed by the sanctioning body. Non-sonic restrictors will influence the output power over the entire rpm range, while sonic restrictors only reduce power once the air flowing through the restrictor starts to choke at higher engine rpm.

The power output for turbocharged engines is typically controlled by a boost limit, or a boost limit curve where increasing boost pressure results in a power increase and reducing boost pressure reduces output power. A boost limit applies a single maximum boost level across the entire engine rpm band, while a boost limit curve assigns a maximum allowable boost as a function of engine rpm. A boost limit acts in a similar manner to a non-sonic restrictor in that the limit has an impact across the entire rpm range. A boost limit curve allows a sanctioning body to shape the power output across the rpm range. With boost limit curves, it is possible to add or subtract power where it is needed, which is a highly desirable function from a BoP perspective.

Fine tuning

In my personal experience, I have been able to successfully align the power outputs of normally aspirated and turbocharged cars by first ensuring the power outputs of the normally aspirated cars are matched using inlet air restrictors, and then fine tuning the output power of the turbocharged cars by tuning their boost limit curves.

Engine power output is influenced by several other factors that may be used to balance vehicle performance. For example, sanctioning bodies may specify ignition angles to increase or reduce spark advance and impact the engine's power output. Likewise, an air / fuel ratio (lambda) may be specified to control the fuel delivered to an engine to add or reduce power.

In cases where the engine ECU is locked or cannot be reprogrammed, it is possible to increase or reduce maximum rpm limits to control power output. If this cannot be programmed into the ECU, this would involve a team setting the shift lights higher or lower and the sanctioning body scrutinising the shift rpm through further data analysis following a session or event.

For a 500bhp vehicle, a good rule of thumb is that a 10bhp change in power output will result in a 0.31 per cent change in lap time (once again, on a 100-second lap). Of course, this factor is highly dependent on the circuit layout, as there are circuits that are much more sensitive to power than others.

Even the tyre manufacturers themselves have to be careful not to cool or cook tyres in transit to the track as either one of these conditions can have a fundamental effect on the racecars' performance

With boost limit curves, it is possible to add or subtract power where it is needed, which is highly desirable from a BoP perspective

Minimum ride heights

We say 'minimum' ride height because a sanctioning body will typically want to try and restrict a car from going any *lower* than the minimum prescribed ride height. These ride heights are typically static, so there is nothing stopping the vehicle from going lower dynamically while on track.

Unfortunately, minimum ride height regulations can have unintended consequences on vehicle set-ups. Teams may start to introduce elaborate bump rubber, spring and damper settings as a way to pass the minimum ride height rules during technical inspection, but to still achieve a desired dynamic ride height while on track.

Ride heights have several impacts on vehicle performance. For all vehicles, increasing or decreasing the minimum ride height will impact the c of g height of the vehicle dynamically. An increase in c of g height causes increases in lateral and longitudinal load transfer when accelerating laterally and longitudinally. Increased load transfer tends to degrade vehicle performance because of the influence it has on the vertical tyre loads when accelerating. For example, a higher c of g in cornering causes a significant reduction in the vertical load acting on the inside tyres that acts to reduce the total lateral force the tyres can generate across the axle. As we have already seen, a reduction in lateral force on the tyres reduces the lateral acceleration capacity, which results in a slower cornering speed.

For aerodynamic cars, changes in ride height influence both the total downforce and the total drag. In most cases, increasing ride height causes a reduction in available downforce. This then has an impact on the vertical loads on tyres acting to reduce the lateral or longitudinal force the tyres can generate. The opposite is true for reducing ride heights. So, increasing minimum ride heights can have the effect of increasing lap times due to reduced aerodynamic forces.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-1.8 MPH
TURN ENTRY
+8.8 MPH
MIN SPEED
+0.7 MPH
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On aerodynamic cars, BoP can be achieved by adjustments in minimum ride height, which has an attendant effect on downforce and drag, and consequently lap time

The combined c of g and aerodynamic effects of minimum ride heights make it extremely difficult to have any sort of rule of thumb for these changes.

Aerodynamic elements

Aerodynamic devices are often used to control the downforce or drag of a vehicle. Downforce has an impact mostly on the cornering and combined acceleration components of a circuit, while drag mostly impacts the straight-line speed of a vehicle.

While we've already addressed the influence of ride heights, the aerodynamic properties of a vehicle may be changed with wing angles, wickers or Gurneys, dive planes, splitters and the myriad other potential aerodynamic elements that may be attached to or removed from the vehicle. There is usually no free lunch with aerodynamic devices, so you cannot add more downforce without increasing drag, or reduce drag without reducing downforce. So, this needs to be taken into consideration when modifying the aerodynamic characteristics of a vehicle.

For properties such as wing angles, a sanctioning body may prescribe a range in permissible angles, or define a minimum allowable wing angle. In general, increasing a wing angle acts to increase the downforce on a vehicle while also increasing the drag. Whether or not this change makes the car faster or slower depends on the sensitivity of the circuit to changes in downforce and drag. As there are circuits that favour higher engine power, there are circuits that favour higher downforce at the expense of increased drag.

Another simple element that can be changed to influence downforce and drag is a wing wicker or Gurney. In most cases an increase in Gurney height increases drag while increasing downforce. I have used Gurney height as a tool to manage a vehicle's top speed on several occasions.

Highly specific

The impact of all the various aerodynamic elements on lap time is highly specific to each device, so again it is exceptionally difficult to have any kind of general idea that may be applied to most situations.

Fuel capacity

Fuel capacity is perhaps the exception here as it does not fit very well with the discussions on Newton's Second Law, but it does have a significant impact on the outcome of races. Fuel capacity defines how far a vehicle can go between pit stops. In many cases, especially where tyre warmers are not allowed, there are significant gains to be made by going one or two laps further on fuel stint.

Likewise, in series where full course yellows can interrupt green flag running, there is a definite advantage to being the first car to pit last. As such, teams and manufacturers demand equality when it comes to how far they can travel on a full tank of fuel. Of course, driver technique and fuel maps still come into play to determine how far one can go, and both have a big influence, but it is important that everyone is on a level playing field to start with.

The impact of various aerodynamic elements on lap time is highly specific to each device

Tyres

Tyre dimensions and specifications are not something that change often in BoP tables, but these changes may still occur. For example, I have experienced times when a new tyre for a car simply does not work with the vehicle, and a reversion to an older specification was required. In addition, I have seen changes to tyre specifications where the tyre dimensions are increased or reduced to influence the cornering capacity of a vehicle. Again, these changes are rare, but they do occur so should still be noted.

In Part 2 of this feature, we will expand upon the base knowledge we have covered in this article and start to look at what it takes to understand *when* changes are required, and what changes are made to solve specific Balance of Performance problems.

Inch pincher

With partner, Interscope Racing, Porsche entered the 1980 Indy 500 to win it, but a matter of inches dictated it never even made it to the grid

By WOUTER MELISSEN

It had fallen victim to a combination of Porsche being Porsche and Indy being Indy

On 6 December 1979, Porsche's director of public relations and sports, Manfred Jantke, invited the German media to the Intercontinental Hotel in Stuttgart to announce the plan to compete in the 1980 edition of the Indy 500.

For the German manufacturer's first foray into American single-seater racing, long-time customer, Ted Field, and his Interscope Racing team was chosen as partner. Porsche would supply the engine and gearbox, while Interscope Racing would design and build a chassis for it.

A few days later, Jantke spread the same message to the American press at an event in New York. However, come May 1980, there was no sign of the promised Interscope Porsche Indy car. It did exist, but it had fallen victim to a combination of Porsche being Porsche and Indy being Indy.

One of the few motorsport arenas in which Porsche had not achieved success, the German manufacturer sent a delegation to the 1977 edition of the Indy 500. It was already decided that Porsche would enter American single-seater racing, but only as an engine supplier to an existing team.

Back burner

During the previous couple of years, Porsche's Can-Am partner, Penske, had sent regular briefings to Weissach, in particular on the performance of the then dominant Offenhauser four-cylinder engine. But, for a variety of reasons, the dream partnership with Penske at Indy did not materialise, and the project was temporarily placed on the back burner.

Out of sheer curiosity, in late '77 the engineering team led by Helmut Both did run a 935 engine on Indy's mandated methanol, just to see what effect it would have. While the results were promising, Both's engineers returned their focus to a further development of the 935 engine for the latest evolution of the 936 Group 6 Sports Prototype, and the all-new 935 'Moby Dick' Group 5 car. This engine was quite a departure from the design that had already proven so successful.

While the production-based crankcase and air-cooled cylinders were retained, a completely new head was developed. Not only did it have twin overhead camshafts and four valves per cylinder, it was also water cooled. The change in cooling philosophy was both a requirement for the additional camshaft and valves and because packaging was so tight that Porsche's tried and trusted air cooling would not suffice.

This particularly affected the spark plugs, which were moved from the airflow

Sharp nose and fully shrouded suspension was designed to allow clean airflow through to the tunnels beneath the full-length sidepods

into the area between the camshafts. Both's engineers did find time in their already busy schedule to also try this engine on methanol as well, just in case.

With the new 24-valve engine in the back, the Porsche 936 could not quite take a third win in a row at Le Mans in 1978, and Porsche decided to wind down its factory Sportscar racing effort at the end of the season. This freed up time and resources to take another look at the Indy 500.

Suitable partner

Before any further work was done, the first task was to find a suitable partner to build and run the car for the proposed Indy engine. Penske was committed to Cosworth's new DFX V8, so instead, California Porsche distributor, Vasek Polak, pointed the Porsche people toward Interscope Racing. The team ran a Parnelli chassis with Cosworth power at Indy in 1978 for Danny Ongais. More importantly, Field and Ongais already had a Porsche connection, running 935s in the American IMSA series. At the start of 1979, they added to their credentials by winning the Daytona 24 Hours outright in their latest 935, with Porsche's Hurley Haywood as the third driver in the winning car.

What Interscope Racing promised was a purpose-built chassis that would be ready in time for the 1980 Indy 500. Hired to help design the car was Roman Slobodynskyj. The Ukrainian-born engineer had been responsible for several successful racers during the 1970s, including the 1973 Indy 500-winning All American Racers (AAR) Eagle.

Like AAR, Interscope Racing was based in Santa Ana, California and, while the 'Interscope IP-1' was being readied, the team modified one of its existing Parnellis to house the engine under development at Porsche in Weissach. Although several years old at this point, the Parnelli chassis was still competitive, underlined by Ongais' fourth-place finish at the 1979 Indy 500, using the Cosworth DFX V8.

Codename 935/72

Back at Weissach, the Hans Mezger-lead team, which included engineers Helmut Flegl and Valentin Schäffer, started the development of the new Indy engine, codenamed 935/72. As that name suggests, it was a development of the flat six that powered the successful 935 and 936 racers. First order of business was to bring the engine down to the 2,650cc displacement limit set by Indy regulations. The bore was 92.3mm, stroke was 66mm.

What the earlier experiments with methanol had revealed was the fuel was considerably more corrosive, so some components had to be constructed from different materials, or specially coated to withstand the effects of this.

An advantage of methanol, of course, is it runs considerably cooler than petrol. To such an extent that the auxiliary fan usually used to cool the cylinders could be eliminated entirely. As on the 935/78 and 936, the cylinder heads were water cooled.

Knocking was less of an issue too, which allowed compression to be raised by two points to around 9.5:1. The change to methanol also required a much higher fuel flow, for which even the injection pump of the 917 did not suffice. Bosch stepped in and developed a fully electronic injection system.

Pressure point

As per regulations, the 935/72 flat six was fitted with a single Garrett turbocharger. The big question that remained during the development of the engine was at exactly what intake boost pressure the regulators would allow it to run. In unrestricted form, it was capable of churning out over 900bhp.

No 'six' had been used at Indy since the early 1950s, so there had been no reason to set a figure. This was measured in inches of mercury and the Offenhauser 'four' could run at 60, while the Cosworth DFX V8 was restricted to 48. Working on the assumption that their new engine would fit smack in the middle of the two, Porsche's engineers expected their 'six' could be run at 54in of mercury. As it turned out, nothing at Indy is quite so straightforward.

The first 935/72 engine was shipped to the Santa Ana workshop in the autumn of 1979. It was mated to a purpose-built Porsche gearbox with Hewland internals. The casing featured all the necessary subframe mounting points to install the engine. This was a special requirement as the Porsche flat six could not be used as a stressed member, like the Cosworth DFX. The weight of these additional structures was offset by the fact the compact flat six was 60lb lighter than the DFX.

The Porsche-engined Parnelli was wheeled out for a first two-day test at the

The twin ground effect tunnels could better be seen from the rear, exiting either side of the equally shrouded gearbox

In unrestricted form, [the 935/72 engine] was capable of churning out over 900bhp

Designed by Roman Slobodynskyj, the Interscope IP-1 was a radical departure from the Parnelli chassis it replaced

The very clean lines were a reflection of the ground-effect revolution that had kicked off in Europe a few years earlier

Ontario oval on 10 October. Ongais, true to his Danny 'on-the-gas' nickname, went straight out and clocked a fastest lap of 197mph. This was a promising start, and prompted Porsche to free up more resources.

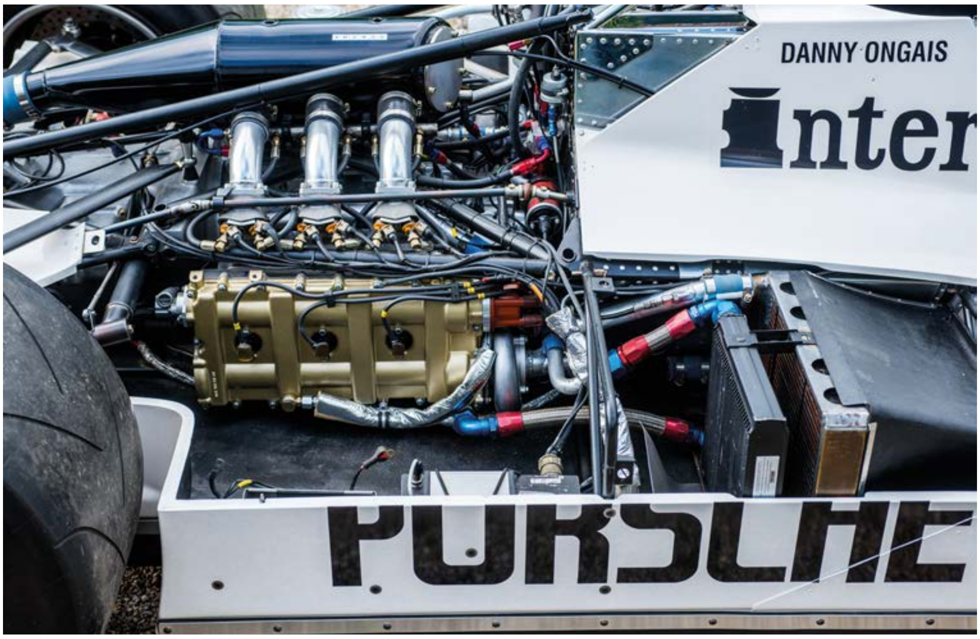
At that first test, the engine ran on 72in of mercury as the final figure was still not clear. It was a subject of debate between more than two parties as Porsche's entry into North American racing coincided with the falling out between the newly formed Championship Auto Racing Teams (CART) and the United States Auto Club (USAC). The regular season races now fell under the stewardship of CART, while the crucial Indy 500 was sanctioned by USAC. This was the race Porsche wanted to win above all, so the conversation over boost pressure took place with USAC president, Dick King. He was keen to put up a good show and also to support the smaller teams that could not afford the expensive DFX engine. This is why the readily available Offenhauser engine was allowed to run at a relatively high level of boost.

Memory game

However, with Porsche's championship-destroying campaigns in Can-Am and IMSA still fresh in their memory, King and the rest of USAC were not inclined to giving the German manufacturer too much leeway.

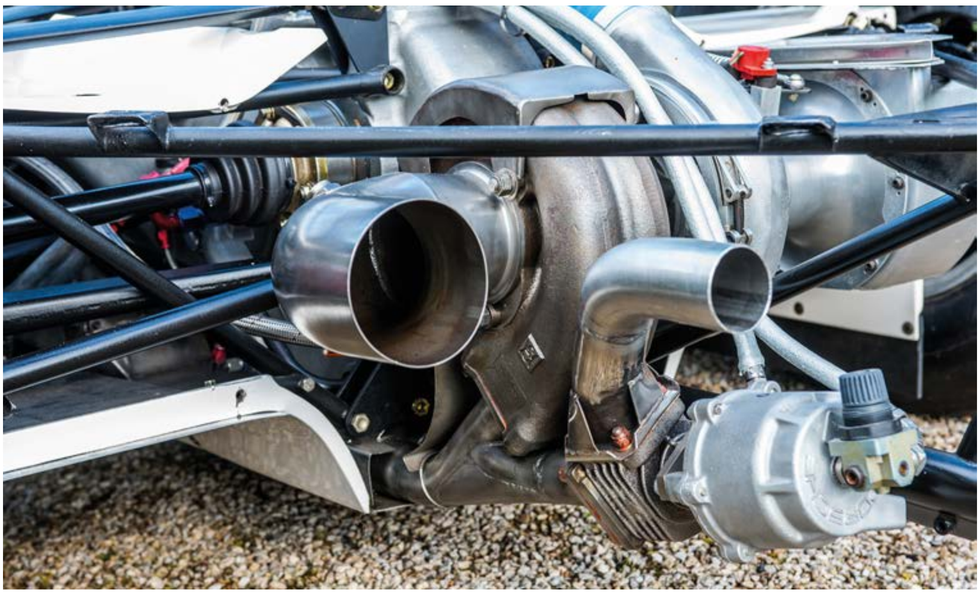
Appointed to liaise with King was Porsche's North American Motorsports chief, Jo Hoppen. In order to keep close tabs on exactly what was happening at Weissach, King requested further information on the engine Porsche intended on running. Initially, he received some very basic drawings that Helmut Flegl had passed on to Hoppen, with the promise of more detail to come. Flegl did send performance figures to Hoppen, but these never made it to King, which left the Americans warier still, and explains why it took so long for a final boost figure to be set.

While the political game was played, back at the Interscope facility in Indiana, the first of the purpose-built racecars was being readied. Designed by Slobodynskyj, it was a complete departure from the design of the Parnelli used by the team previously. The very clean



2650cc flat six was a development of the succesful Porsche 935 / 936 engine, but with raised compression and fed methanol


Rear bodywork of the car was so low that the upper suspension wishbones actually ran above it


A single Garrett turbocharger was used, but it all hinged on the intake boost pressure the 935/72 engine was allowed to run

lines were a reflection of the ground-effect revolution that had kicked off in Europe a few years earlier. Accordingly, the Interscope IP-1 featured a sharp nose to allow for a clean airflow to the tunnels mounted underneath the full-length sidepods. The front suspension was fully shrouded, while the rear bodywork was so low the top wishbones ran above it. The tail was dominated by the two ground-effect tunnels either side of the gearbox.

Testing with the Parnelli chassis resumed in January, with the engine now running at the proposed 54in of mercury boost pressure. Although these were private tests, some rivals went as far as to hire a helicopter to see what Porsche was up to.

Ahead of his final decision, King proposed to send a delegation to Weissach and asses the engine development at the factory. Porsche agreed, but was more than a bit surprised to find one of the delegation members was the engine man of the rival AJ Foyt team. The Germans showed the American delegates an engine running on the dynamometer, which produced 574bhp with 54in of boost. This was an output that matched the rival engine, so Porsche engineers figured the matter had now been resolved once and for all.

Development room

Early in March, the matter was indeed resolved, but not to Porsche's liking. The USAC set the boost level for the Porsche engine at 48in of mercury, the same figure as the Cosworth DFX V8 that had been designed from the ground up as a racing engine, and some six inches less than the Porsche engineers had been expecting. King reasoned there was sufficient room to develop the Porsche engine further for it then to be as competitive as the DFX.

Should the performance of the Porsche engine turn out to be not at the same level as its rivals during the races, USAC promised the decision could be reconsidered.

King's decision was a devastating blow to the programme. At 48in of mercury, the engine would produce no more than 540bhp, which would leave the team playing catch up at the back of the field. For a company like Porsche, that was not an option.

In truth, there was some merit in King's suggestion that – in theory at least – a flat-six engine *could* perform better with further development. This would, however, entail a complete redesign of the engine, with the engineers effectively starting again from scratch. Porsche was not inclined to do this for a variety of reasons, including a lack of time and resources. Consequently, on 23 April, Porsche officially announced its entry into the 1980 Indy 500 had been scratched.

After Le Mans, when the dust had settled a little bit, the programme was re-assessed.

Up to four IP-1 chassis were constructed, but none ever raced at Indy with Porsche power. This is the only known example

It was decided to resume testing in July, the engine now mounted in the Interscope chassis. Porsche even reputedly considered running the car in a race at Mid-Ohio, but that was later called off.

Testing continued on into September, and the Porsche-powered Interscope was really coming on song. Meanwhile, back at Weissach, a new short-stroke engine was also drawn up, which should be able to perform better with the lower boost level. Sadly, the Porsche board had seen enough by this point, and decided to suspend the Indy programme indefinitely in October of 1980.

Great things

For Porsche, the whole saga turned out not to be a complete waste of time. A development of the 935/72 engine was destined for truly great things. Modified to run on petrol once again, and re-fitted with a cooling fan, it appeared the following year in the back of a pair of Porsche 936s entered in the 24 Hours of Le Mans. Now known as the 935/82, the 2.65-litre engine powered the 936 shared by Jacky Ickx and Derek Bell to the outright win, with a 14-lap margin over the nearest rival.

The 'Indy engine' was then fitted in the 956 Group C racer that was introduced in 1982. The rest, as they say, is history.

Porsche did have another go at Indy a decade later, but once again with little luck.

The Interscope team was left to pick up the pieces. It is believed as many as four IP-1 chassis had been manufactured by the time Porsche pulled the plug and so, for the 1981 season, the team switched back to Cosworth DFX power. This allowed Ongais to run at Indy once again, an opportunity he relished. He qualified on the seventh row and, by lap 63, was in the lead. A delay during the next

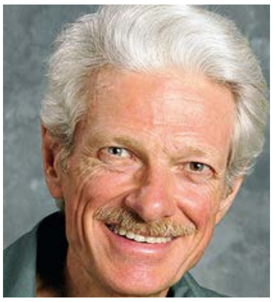
Porsche… was more than a bit surprised to find one of the delegation members was the engine man of the rival AJ Foyt team

pit stop forced him to claw back up the order and take one risk too many. Over-correcting a slide, he hit the wall head on and destroyed the car. He was lucky to come out of the crash with nothing more than concussion and badly broken legs and feet.

He returned the following year but, once again, suffered a near career-ending crash after starting from the third row this time. That was the final appearance of the Interscope chassis, as the team switched to March chassis from 1983 onwards.

Long believed to be lost, one of the remaining Interscope chassis was discovered in a shed in Santee, California by a German enthusiast in 2008, still fitted with the ancillaries to house the Porsche engine. Finding one of the 10 935/72 engines built proved even more difficult and took several years. The restoration was further delayed by a lack of documentation, but it was finally completed in 2020.

The car shown here is believed to be the only Interscope Indy car in existence, and certainly the only fully functional, Porsche-engined example. Intended to run at the now cancelled 2020 Goodwood Festival of Speed, the car is currently for sale with German dealer KW - Klassische Automobile.



Sunshine on leaf

Hop, squat, lift, wrap and other issues in leaf spring, live axle rear suspension

By MARK ORTIZ

Q I am building a 'somewhat vintage reproduction' track car for the Barber Road Course. It would be best compared to the Camaros and Mustangs that raced the Trans-Am circuit in 1969-'70.

The brake package and front steering / suspension is modern and very robust. However, the rear suspension is slider-mounted, 200lb/in, Chrysler-style stacked leaf springs with a Panhard (though I plan to try a composite monoleaf at some point in time).

The sliders on the rear of the springs will give me up / down and / or angular adjustment, and are within the rules. Bird cages / links and floating calipers seem unnecessarily complicated to me and are more than I want to deal with, or package on this car.

I know there are probably better ways to skin the cat, but I have always had a fascination with leaf springs and the tuning thereof (ie changing wheel rate / linearity etc. by changing mount geometry and the possibility of 'tuning' wheel rates without changing the springs).

I have been warned that brake hop could be an issue (?) and so, having talked to the engineers at Landrum and Hypercoil, have included brackets for 'anti-hop' shocks. These will allow for two shocks per rear assembly for up / down and either one or two, probably 90/10s, to 'anti' the brake torque.

Some guys swear a leaf set-up will induce rear-end steer ie the more loaded side of the car will have a longer wheelbase than the less loaded side. Supposedly, non-parallel leaf springs enhance this effect.

Although, I would add that Bobby Allison had the track record at Huntsville Speedway (asphalt) from about 1975 to 1985 with a quarter elliptic leaf spring set-up, and everyone said that was a rear-end steer car.

Then there is the esoteric 'bite effect' that some claim a leaf set-up has. Does this have something to do with the 'wheelbase effect' or is it just race mythology?

With its Ford Windsor 'N'-type engine (about 580bhp) and a Roltec synchronised 4-speed, the car should be about 2700lb, with 50/50 distribution, adjustable brake bias and 12.19in GN6-type front brakes.

What are your thoughts on this set-up?

The questioner's 'somewhat vintage reproduction' road course car uses slider-mounted, Chrysler-style leaf spring packs

THE CONSULTANT

A Certainly, you can get rear roll steer with leaf springs, just as you can with links. It's mainly a matter of how high the front eye is with respect to the pad on the axle, plus the characteristics of the spring itself.

As for having the springs non-parallel in top view, I don't think that necessarily affects roll steer, but it affects compliance steer. Leaf springs are laterally compliant, especially with shackles, and if the springs are toed in that gives compliance oversteer. It also can create steer effects when a sloped Panhard bar creates lateral axle movement, as with truck arms.

Eliminating the lateral compliance in the shackles is the usual reason for using sliders, and also the reason for adding a Panhard bar. It is unusual to do both as you don't want two methods of lateral location fighting each other and creating a bind.

You can make sliders adjustable for angle, and also height, although the few slider set-ups I've seen were fixed. You can do the same with shackles, though. Mechanisms with sliding contact tend to have more friction than things that move rotationally about a pivot, and are more vulnerable to jamming from dirt and gravel.

One effect of the short front, long rear Chrysler-style spring is it gives some anti-squat and anti-lift. A spring with similar front and rear portions acts sort of like

Leaf springs are laterally compliant, especially with shackles, and if the springs are toed in that gives compliance oversteer

parallel trailing links, with soft rubber bushings. The Chrysler style acts like trailing links that converge toward the front, again with soft rubber bushings.

The usual idea with horizontal shocks above the axle is to damp spring wrap-up. They are also used to damp oscillations in link suspensions with soft bushings, as on some Fox-body Mustangs.

That can be one cause of wheel hop in braking, but another can be having a lot of anti-lift. Chrysler-style springs give more anti-lift than others, for the same reason they give more anti-squat.

The relatively rigid front portion of the spring acts a bit like a ladder bar.

Side View Instant Centre

Without some computer programme that probably exists but I don't have it, you can't know exactly how much anti-squat and anti-lift your springs will give you when you're designing your system. However, I do know a way to find out what effective side view instant centre (SVIC) your system produces, once you've got it assembled on your frame, and that will tell us how much anti-squat and anti-lift you have.

To do this, measure your pinion angle gain, just as you would measure camber gain on your front end – put an angle finder on the companion flange, or any convenient surface. Then jack the whole axle up and down, and measure how much the pinion angle changes per inch of travel. To do this with the springs in place, you'll have to find a way to hold the car down. Ordinarily, you do this with the springs out, but of course when the springs locate the axle that's not possible.

To get the best approximation of what you have at static ride height, take a one-inch interval from ½in droop to ½in bump. Divide 57.3 or 180/pi by the number of degrees of pinion angle change. That's the horizontal length of your effective side view swing arm, or horizontal distance from the axle centre to the side view instant centre.

Now you also need the height of that instant centre. To find this, you need a way to measure longitudinal (x axis) translation of the axle as you jack it up and down (dx / dz). This may be a pretty small movement. Probably the cheapest and easiest way is to place a machinist's scale on the floor and drop a plumb bob to it from the front or back face of the axle tube. From this you get inches of forward or rearward translation per inch of vertical travel. That number is also the slope of a line from the axle centre to the instant centre, upward if the axle moves back in compression, downward if it moves forward in compression. The SVIC lies on that line, at the horizontal distance forward that you measured per the preceding paragraph.

Armed with those measurements, it is possible to tell how much anti-squat and anti-lift you've got in a suspension system, and whether that's apt to cause wheel hop. Note that wheel hop from this cause can't necessarily be solved by damping spring wrap-up.

Bite effect

Regarding the 'bite effect' you mention, I don't rightly know. I interpret 'bite' as the ability to apply throttle without wheelspin.

The quarter elliptic set-up you mention? Was it perhaps a leaf car with just the top leaves, but a stack on the front half of the left one, and coils or coilovers mostly supporting the car? I've seen that done successfully on a WISSOTA modified. That produces what some might call a 'bite effect' ie under power, it gives strong anti-squat at the left rear, adding 'bite' in the sense of wedge or diagonal percentage. The effect is similar to the offset torque arm on a Super Modified.

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I accept this diagram is from memory, and you note the rear housing may have been on the top side of the spring, with the spring arched downward, rather than as per the illustration.

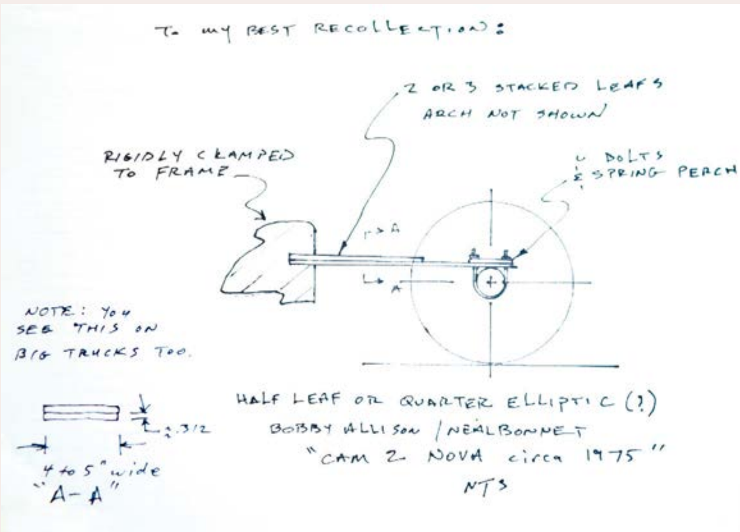
That said, the quarter-elliptic set-up as you have drawn it here would not work. It would fail the lower leaf instantly. You can run cantilevered quarter-elliptics with the thick end clamped to the frame, but you have to have an eye at the axle, and at least one additional link to react torque, so that torque loads the spring in tension or compression, not bending. That's assuming two springs, one on each side of the car.

To use the spring to react torque in bending, you must have the thick part at the axle, where the bending moment is greatest. Even then, you cannot clamp the thin end of a leaf spring as you will have a bending stress concentration at the edge of the clamp. You must have an eye or a drop link at the thin end – something that can pivot. Even sliders have to have those pins that can rotate in the slots, or an eye with a bushing.

The systems used on large trucks, at least currently and recently, have a spring on each side, each having two or three really thick leaves with the thick end clamped to the axle. The spring has an eye at the front end with a big, soft rubber bushing. The spring extends behind the axle and serves as an air bag mount, and it is the air bags mainly that support the truck. In this situation, the leaf spring serves as a sort of compliant ladder bar.

The whole set-up also acts as an anti-roll bar. As with other ladder bars, either the bars (springs) have to flex, or the axle housing has to twist, for the suspension to move in roll. This is important because the air springs are connected and therefore cannot resist roll, although they damp it somewhat. There is also a very high-mounted Panhard bar for lateral location.

These truck suspensions provide a lot of anti-squat and anti-lift. The truck can be seen to jack visibly when launching from rest, and wheel hop can occur in braking, especially when running without the weight of a trailer. There is also a lot of torque roll under power.



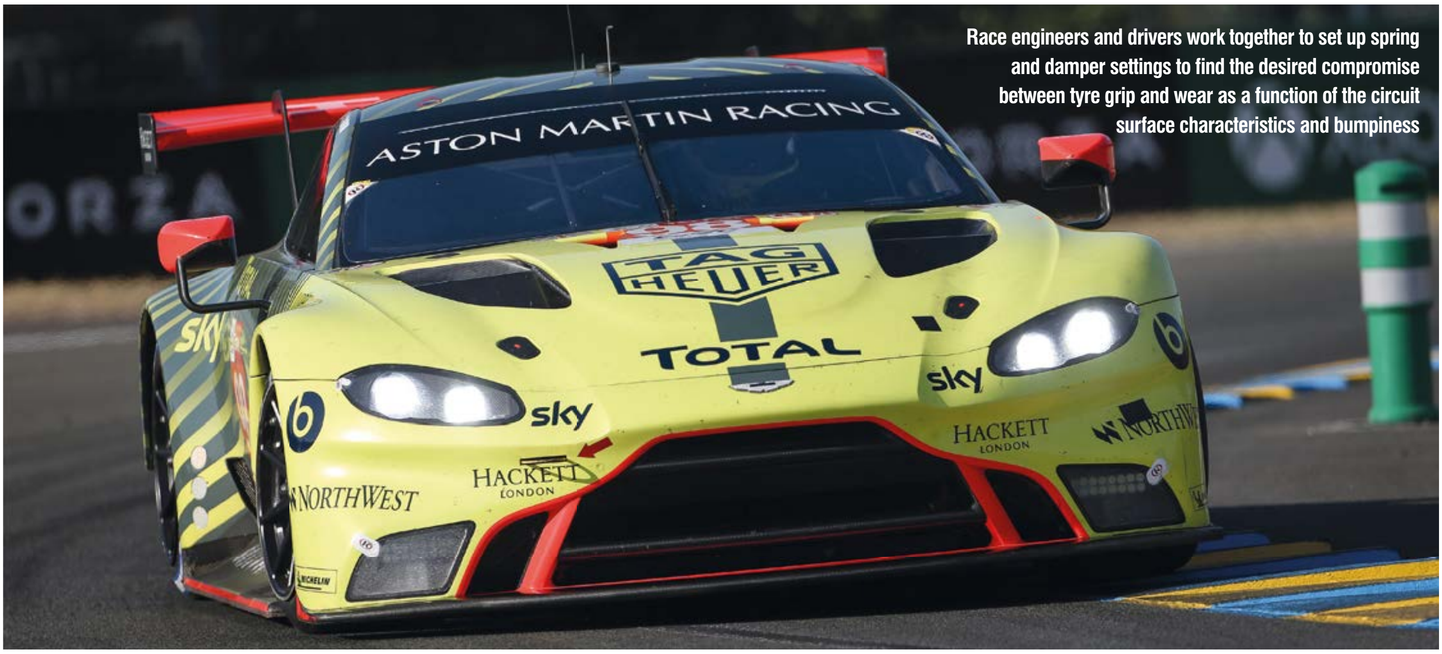
Do not copy this, it will not work without an eye at the axle and at least one additional link

To be continued next month…

Of springs and dampers

The meaning and usefulness of suspended mass natural frequency numbers

By CLAUDE ROUELLE



Race engineers and drivers work together to set up spring and damper settings to find the desired compromise between tyre grip and wear as a function of the circuit surface characteristics and bumpiness

In the last article we stated that spring stiffness choice is based on experience and subjective appreciations, as much as it is on objective science. The determination of the spring stiffness is dependent of the track macro (bumps, kerbs, slope, banking) and micro (asphalt roughness) definitions, the track temperature, the car mass, inertia and aerodynamic properties, the tyre (in itself a dark science) grip, wear and thermal characteristics, the effects that suspension stiffness can have on the car reliability and, finally, driver skill.

Most of these inputs are not easily qualifiable and quantifiable. However, there are two fundamental engineering tools that we can bring into our decision process.

Shapes of things

The first one is the definition of track bumpiness. What are the shapes of the track bumps and how often, and at what speed, do the tyres hit these bumps? This will help in the spring stiffness choice. We will discuss this further in a future article on a quarter car model simulation. That simulation tool allows us to define spring and damper depending what the race engineer and driver are looking for, and the compromise they will accept between tyre grip and wear, ride height consistency and its effect on aerodynamic performance and expected response.

The second one is simply a determination of the suspended mass natural (undamped) frequency. The basic formula for this is

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

where,

K is the wheel rate expressed in N/m
M is the suspended mass expressed in kg
f is the suspended mass frequency and is expressed in cycles per second or Hertz (Hz)

Put simply, the wheel rate is a 'virtual' spring that represents the effect the spring has at the liaison of the wheel with the ground. Wheel rate will be in series with the tyre rate (or tyre stiffness if you prefer).

The wheel rate, K, is the spring rate divided by the square of the motion ratio.

$$K = Wheel\ rate = \frac{Spring\ rate}{MR^2}$$

The motion ratio is the ratio between wheel movement and spring movement, as explained in more detail in the box below.

Some people have difficulty understanding the reason for the use of the square of the motion ratio to calculate wheel rate from spring stiffness. Here is a simple explanation. If you take the principle of conservation of energy you can write that

$$(Force\ to\ move\ the\ wheel\ up) * wheel\ travel = (Force\ to\ move\ the\ spring) * spring\ movement$$

That equation supposes there isn't any friction in the rod ends and / or the bellcrank bearings. These frictions always exist in practice but, for the simplification of the demonstration, we will consider them negligible.

As the spring force is nothing other than the spring stiffness * , the spring movement in the previous equation can be re-written as

$$(Wheel\ rate * wheel\ travel) * wheel\ travel = (Spring\ rate * spring\ movement) * spring\ movement$$

Or

$$Wheel\ rate = \frac{Spring\ rate}{MR^2}$$

For those still not convinced, **Figure 1** shows a simple sketch extracted from the OptimumG Advanced Vehicle Dynamics seminar that will help full comprehension.

On the left, the real spring, and on the right, the 'virtual' spring that represents wheel rate. In this example, the motion ratio is two, that is to say the wheel moves twice as much as the spring. If wheel movement is double the spring movement, it is as if the 'virtual' spring (wheel rate) is half the spring stiffness. However, as you can see, the force is also half of the force on the spring. So, if we have twice the movement and half of the force, we have a wheel rate that is a quarter of the real spring stiffness. As the motion ratio is two, the wheel rate is the spring rate / 2^2. Hence the use of the *square* of the motion ratio.

Note that the notion of the motion ratio is applicable to the damper too, as illustrated by the sketch in **Figure 2**.

$$Damping@wheel = \frac{Damping\ @damper}{MR^2}$$

Here are a few useful comments and warnings to avoid often made mistakes:

- Spring stiffness is expressed in Newtons per metre (N/m) not in Newtons per millimeter (N/mm). That is a classic error.
- Be aware this equation is for one corner of the car only. Third (heave) springs are not taken into consideration here, nor are anti-roll bars.
- Look at the main formula and keep things in practical perspective. Because the natural spring stiffness is a function of the square root of the spring stiffness, when you double the spring stiffness, you only increase frequency by 41 per cent, because the square root of two is 1.41.
- Do not forget that wheel rate is in series with the tyres (and possibly some badly designed suspension compliance). Springs in series are always softer than their stiffer spring, and you do not double the whole suspension stiffness when you double the spring.

  When your car is not working and you suspect the suspension is too stiff, *or* too soft, changing the spring stiffness by only five per cent will not make a big difference.
- Motion ratio is the ratio between wheel movement and spring movement, not the other way around. We must be careful here as some engineers in specific racing series (NASCAR especially) often express motion ratio as spring movement vs wheel movement. That is not right or wrong, we just need to make sure everybody uses the same definitions in their calculations.

  Be careful, though, because 1.1^2 = 1.21. An error of 10 per cent on the motion ratio (because of non-respect of suspension parts manufacturing tolerance, for example) is an error of 21 per cent on wheel rate.
- On a suspension such as McPherson, motion ratio will always be bigger than one, and the wheel will always be moving more than the spring.
- On a car with a push or pull rod and rocker (some call it a bellcrank) suspension, spring movement can be bigger that wheel movement. The motion ratio in this case will be less than one.
- In most racing suspensions, the spring and damper are assembled in one unit, often called a coilover. The NASCAR front suspension, where spring and damper are not on the same axis, is an exception.
- A motion ratio smaller than one (where the spring and damper move more than the wheel) will generate more spring and damper movement than the wheel, and therefore more spring and damper speed and acceleration.

  For a given wheel up and down movement at a given frequency, we will get the same frequency at the spring and the damper (again, supposing compliance and friction of the rod ends and rocker bearings are negligible).The same frequency but a longer stroke results in higher damper speed and acceleration, whereas with higher damper speed we have more resolution and adjustability.

  To use a very basic example, it will be easier to control wheel movement with a damper that has a speed in a -250 to +250mm/sec window than one with a -50 to +50mm/sec window.

Figure 1: Motion ratio between wheel rate and spring rate

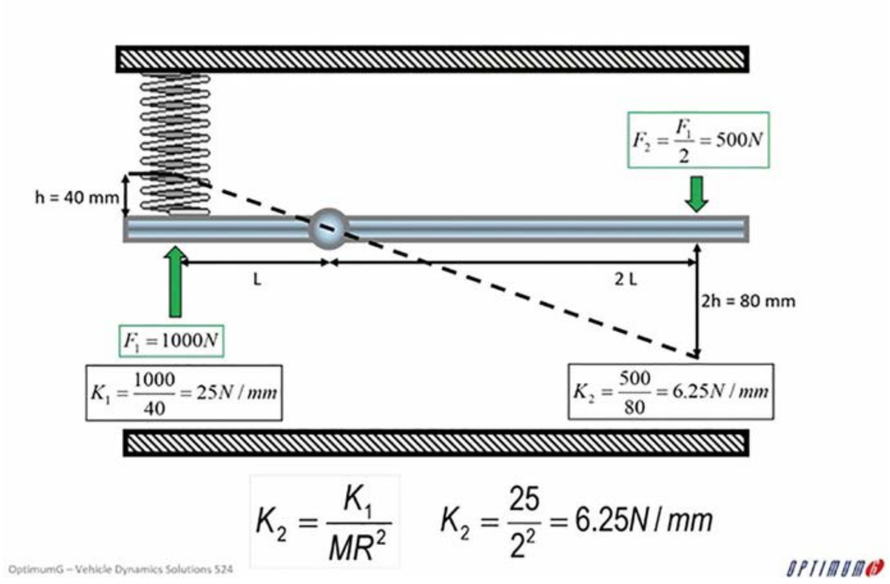
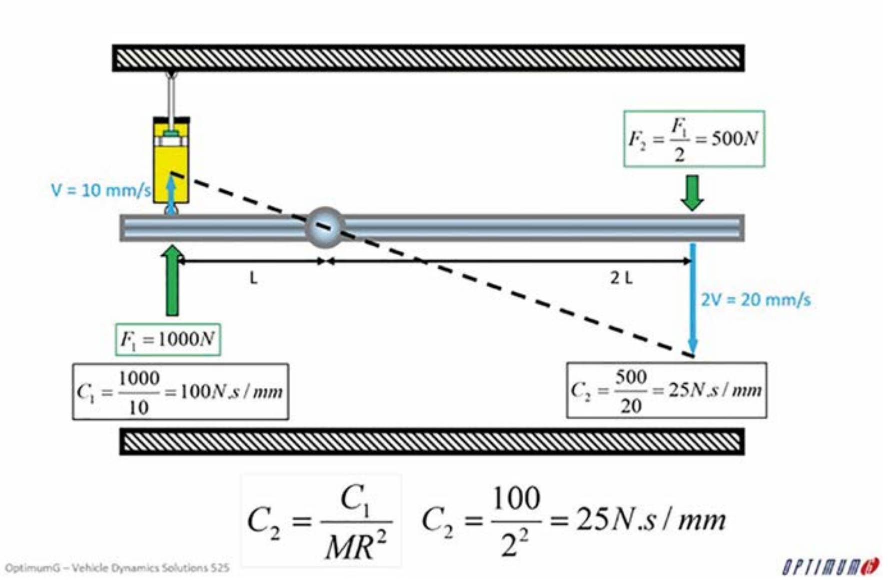


Figure 2: Motion ratio between wheel rate and damper rate



The advantage of the suspended mass natural frequency is it links both masses, kinematics of the motion ratio and suspension stiffness

- At the other end, bigger speed and bigger speed changes (accelerations) create the risk of damper cavitation. Risk of cavitation in a damper can be decreased with higher gas pressure, but at the cost of higher friction.
- As damper force (N) = damping rate (N/(mm/sec)) * damper speed (mm/sec), the same damping force can be achieved with less damping rate and more damping speed (that is achieved with a small motion ratio) than with more damping rate and less damping speed (that is achieved with a high motion ratio).
- For a given wheel movement and given wheel force, a small motion ratio will result in a longer and softer spring and a longer and softer damper, but keep in mind the implications damper and spring sizes and characteristics will have on weight and packaging.

  Small motion ratios seem appealing for their higher speeds and window of adjustments, but impose serious restrictions on the car designer in terms of packaging. Weight and packaging are always bigger challenges in cars like Formula 1 than, say, Baja cars.
- Motion ratio, MR, is not necessarily – in fact rarely – a constant number. By design and / or because of compliance, it is often a function more than a number.
- In fact, a non-linear motion ratio could have some advantage, especially for cars with aerodynamic ground effect. With these, we want a relatively soft suspension at low speed to get maximum tyre grip (we have explained in previous articles how the tyre 'hates' vertical load variation) and a stiff suspension at high speed to maintain a low ride height, despite the downforce that is square of the speed sensitive. There are three ways to achieve this compromise, and they can be used separately or together: variable spring rate (achieved with changing the spring pitch, wire diameter and spring outside diameter along its length), variable motion ratio and bump stops (made of polyurethane or even assemblies of Belleville washers).

  For example, if motion ratio is 0.9 at high ride height (low speed) and 0.8 at low ride height (high speed) with a spring constant stiffness of 400N/mm, wheel rate will vary from 400 / 0.92, which is 494N/mm to 400 / 0.82, which in turn is 625N/mm. That is a 25.6 per cent wheel raising rate. Not negligible, and not something to be ignored.

Spring stiffnesses themselves are rarely constant. If you put a spring on a spring tester, measure the stroke and the force, and make a graph of force vs movement you will rarely get a straight line. Without going into the details of the spring stiffness equation, we will simply remind you that when the spring is compressed, there will be more and more contiguous coils and the spring stiffness increases when the number of active coils decreases. From this point of view, torsion bars offer a more constant stiffness than a regular spring.

Practical constraints

At the end of the day, besides the equations developed here, the choice of motion ratio is most often dictated by practical weight and packaging constraints, and the answer to this simple question: do you design a coilover unit and decide its dimensions and characteristics to adapt it to a given existing suspension, or do you design a suspension around a given damper?

In other words, a Formula 1 car designer imposing damper and spring sizes and characteristics to a subcontractor is a very different story to a Formula Student team that was given a free set of dampers via some sponsorship, and has to design its car's suspensions around the imposed dampers.

Taking the following equations together,

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

$$K = Wheel\ rate = \frac{Spring\ rate}{MR^2}$$

we can define the spring stiffness for a given frequency and a given motion ratio.

$$Ks = 4\ \pi^2\ f^2\ M\ MR^2$$

Where *Ks* is the spring stiffness (N/m), *M* the suspended mass (kg), *f* the suspended mass natural frequency (Hz) and *MR* the motion ratio (non-dimensional).

For example, let's consider a car's left front corner mass (measured on scales) that is 250kg, with a non-suspended mass of 42kg. The suspended mass will therefore be 208kg. If the motion ratio is 0.95 and the targeted natural frequency is 4Hz, the spring will be $Ks = 4\ \pi^2\ \ 4^2\ \ 208\ \ 0.95^2$ = 118,545N/m or 118.5N/mm, or 675lbs/in for our old fashion American friends.

The experience has shown that natural suspended mass frequencies (also called undamped frequencies) are in the following regions: for passenger cars – 1.1Hz (very soft) to 1.8Hz (very stiff); for non-aerodynamic racecars – 1.5-3.0Hz, and for aerodynamic racecars – 3.0-7.0Hz.

Yes, 7Hz seems particularly high, but let's not forget this kind of situation occurs on front suspension of aerodynamic racecars for which front ride height control is critical, and such cars are often seen with an additional third (heave) spring, and most probably the use of bump stops, too.

What's important to note is that each car mass and suspension are different. Each track or rally special stage is different. How then do we compare the suspension stiffness of a heavy racecar with a light rally car? The advantage of the suspended mass natural frequency is it links both masses, kinematics of the motion ratio and suspension stiffness, so it is a common denominator that allows us to compare car suspension stiffness.

But how stiff is too stiff? How soft is too soft? Now we are back to the intuitive and experimental approach describe in our previous article. At least, the suspended mass natural frequency is giving us the beginning of a reference point on the map of development. Or what we call a 'magic number'.

So, when your car works well, be sure to note the front and rear natural frequency. Then, the day you are lost, at least you can go back to this reference.

Slip Angle is a summary of Claude Rouelle's OptimumG seminars, which are held worldwide throughout the year. The Data Driven Performance Engineering seminar presents a number of data acquisition and analysis techniques that can be used by engineers when making decisions on how to improve vehicle performance.

OptimumG engineers can also be found around the world working as consultants for top level teams.

Check out our seminar calendar on the website: optimumg.com/calendar

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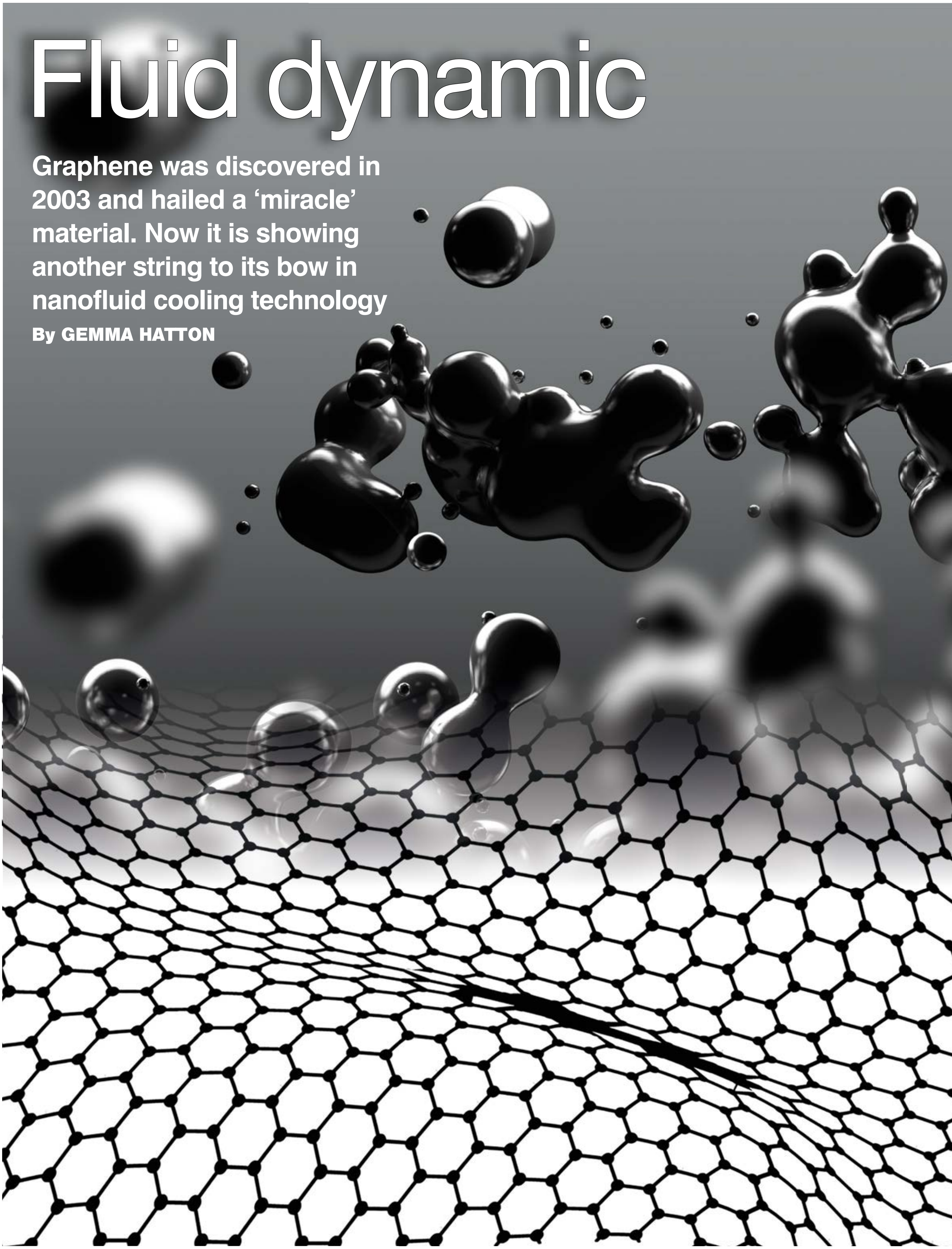
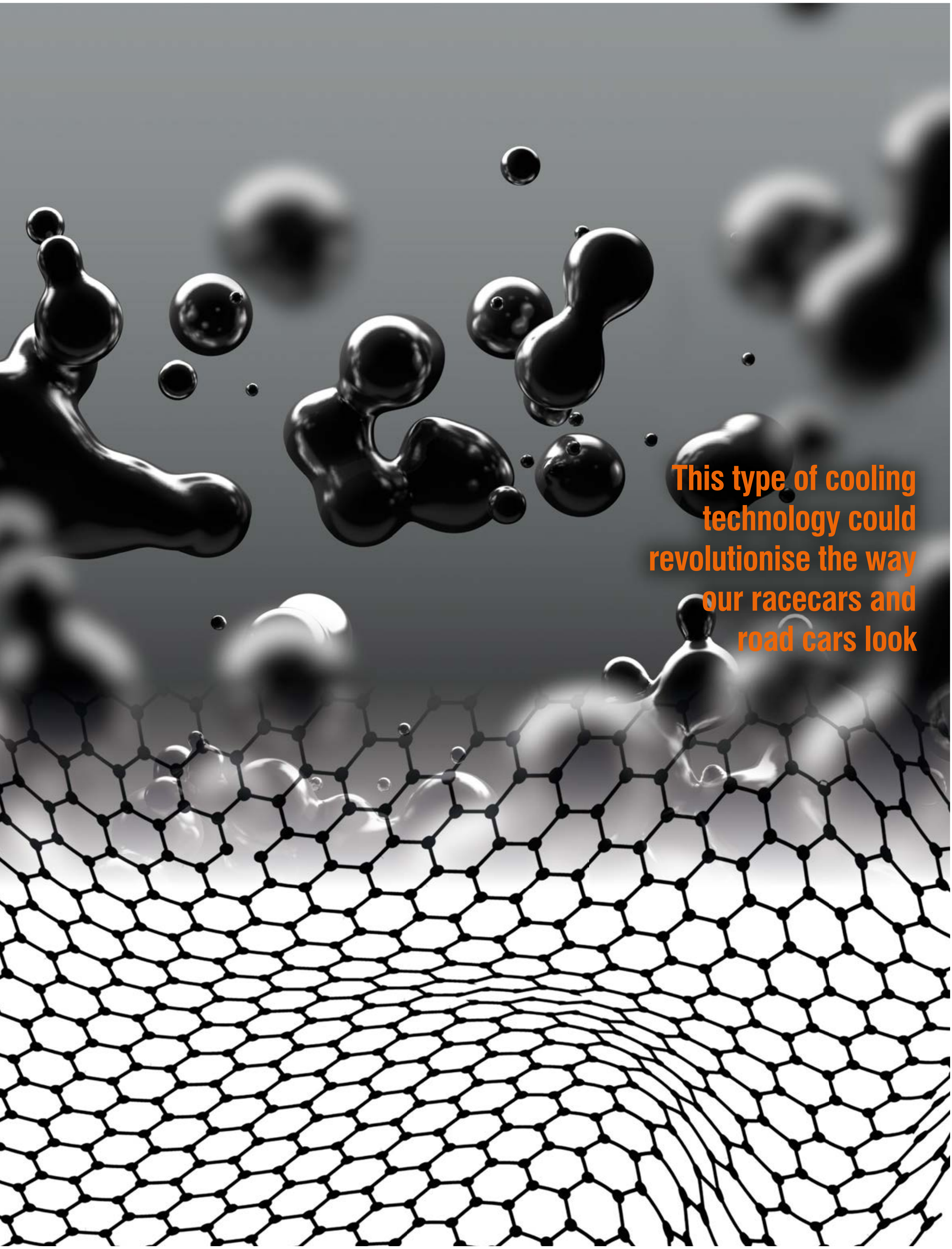
Fluid dynamic

Graphene was discovered in 2003 and hailed a 'miracle' material. Now it is showing another string to its bow in nanofluid cooling technology

By GEMMA HATTON





This type of cooling technology could revolutionise the way our racecars and road cars look

Graphene is a single layer of carbon atoms, or graphite, tightly bound in a hexagonal honeycomb lattice structure. At one atom thick, graphene is the thinnest material on Earth. It takes three million sheets of graphene stacked on top of each other to achieve the thickness of a human hair.

Its perfect crystalline structure and strong interatomic bonds also make it the strongest material on the planet, boasting strengths 200 times that of steel. Despite this, it's also the lightest material, with one square metre of paper weighing 1000 times more than the same size piece of graphene. Not enough? It's also an excellent conductor of electricity, and of heat at room temperature. Perhaps now you can start to appreciate why there is such a hype surrounding graphene, and why it has the potential to revolutionise many industries.

In the motorsport and automotive sectors, graphene has mostly been utilised in nanocomposites, enhancing resin systems through nanoplatelet reinforcement. This is where graphene is mixed into resins, which are then combined and cured with layers of carbon fibre, greatly increasing the inter-laminar bond strength and, consequently, shear toughness. The likes of McLaren and other F1 teams have experimented with graphene in composites, but it is currently banned under the technical regulations, along with carbon nanotubes.

The closest graphene composites have come to motorsport so far has been the BAC Mono (*RE* V28N8), which made BAC the first manufacturer to develop a car incorporating graphene technology. Graphene-enhanced carbon fibre composite panels were used for the rear wheelarches, which not only improved the stiffness of the chassis but also reduced weight by 20 per cent.

Fluid technology

Interestingly, however, it's not just composites that can benefit from graphene's phenomenal properties. Researchers are currently developing methods to coat tyres with layers of graphene to reduce rolling resistance and improve grip. While the material's sensitivity and electrical conductivity, along with its thin structure, makes it perfect for sensors and other electronic components. What you probably haven't heard of, though, is how graphene can also be utilised in nanofluids.

'Graphene has the highest known thermal conductivity of any material, which is about 10,000 times that of a base fluid such as water,' explains Shannon Notley, founder of Flexegraph. 'So by putting small amounts of graphene into these liquids, you can enhance the thermal properties quite substantially.

'It works about 60 per cent more efficiently than traditional cooling fluids, and that opens up a big range of opportunities for advanced cooling applications. Many systems have been conceptualised based on the limitations of the fluid, so changes are made elsewhere within the cooling system. We've been able to help re-focus the whole industry on understanding how we can incorporate these new liquids, and what that means not just for performance, but also the design of cooling systems in general.'

Notley spent a large chunk of his career at the Australian National University, where he researched and developed the technology to suspend high quality graphene particles in liquids for large scale production. Like everyone else, he initially thought developing graphene for composite reinforcement would be the way to go but, with the market already crowded, he opted for nanofluids instead.

'We thought, well, we need to get to market as quickly as possible, what is the easiest product that we can produce? Because we were already producing graphene in water, that's basically 95 per cent of the way to a cooling liquid already. It was pretty much ready to go,' says Notley.

Suspension challenge

Although this sounds simple, graphene is not the easiest material to work with, especially when trying to suspend it in liquids. Historically, graphene was predicted to be too unstable to be produced. It was only when Professor Sir Andre Geim and Professor Sir Kostya Novoselov at the University of Manchester in the UK found a way to isolate it in its pure form in 2003 that it became a material that could be worked with. Suspending it homogenously within a liquid is even more of a challenge.

'It's not an easy thing to do,' confirms Notley. 'Broadly speaking, you have two main categories of material: hydrophilic, which love to be in water, or hydrophobic, which hate being in water and prefer to be in oils. The unique properties of graphene mean it sits right on the border of those two categories. So it doesn't really like water and it doesn't really like oil either. Therefore, you have to tune its properties to get it to be stable within those different liquids, which is not trivial.'

To help achieve the stable suspension of graphene particles within water, as well as tune the specific properties of a coolant,

By suspending graphene in solutions, it is possible to dramatically enhance the liquid's thermal properties

It works about 60 per cent more efficiently than traditional cooling fluids

Shannon Notley, founder of Flexegraph

up to 20 other ingredients can be added to the liquid. 'Each has its own use case to try and improve the performance of the liquid,' explains Notley. 'There will be anti-corrosion additives, anti-microbials, dispersants as well as dyes. You add in all of these components to improve performance, but they can either have a positive or negative effect on stability.

'One of the things we've been working on in particular over the last six years has been how do we make the suspension of particles stable within complex mixtures, whilst coping with the temperature cycling of a traditional internal combustion application over many years for road car applications.'

Road car coolants have to operate in environments ranging from -35degC to 110degC, and for 50-80,000km intervals

Technical challenge

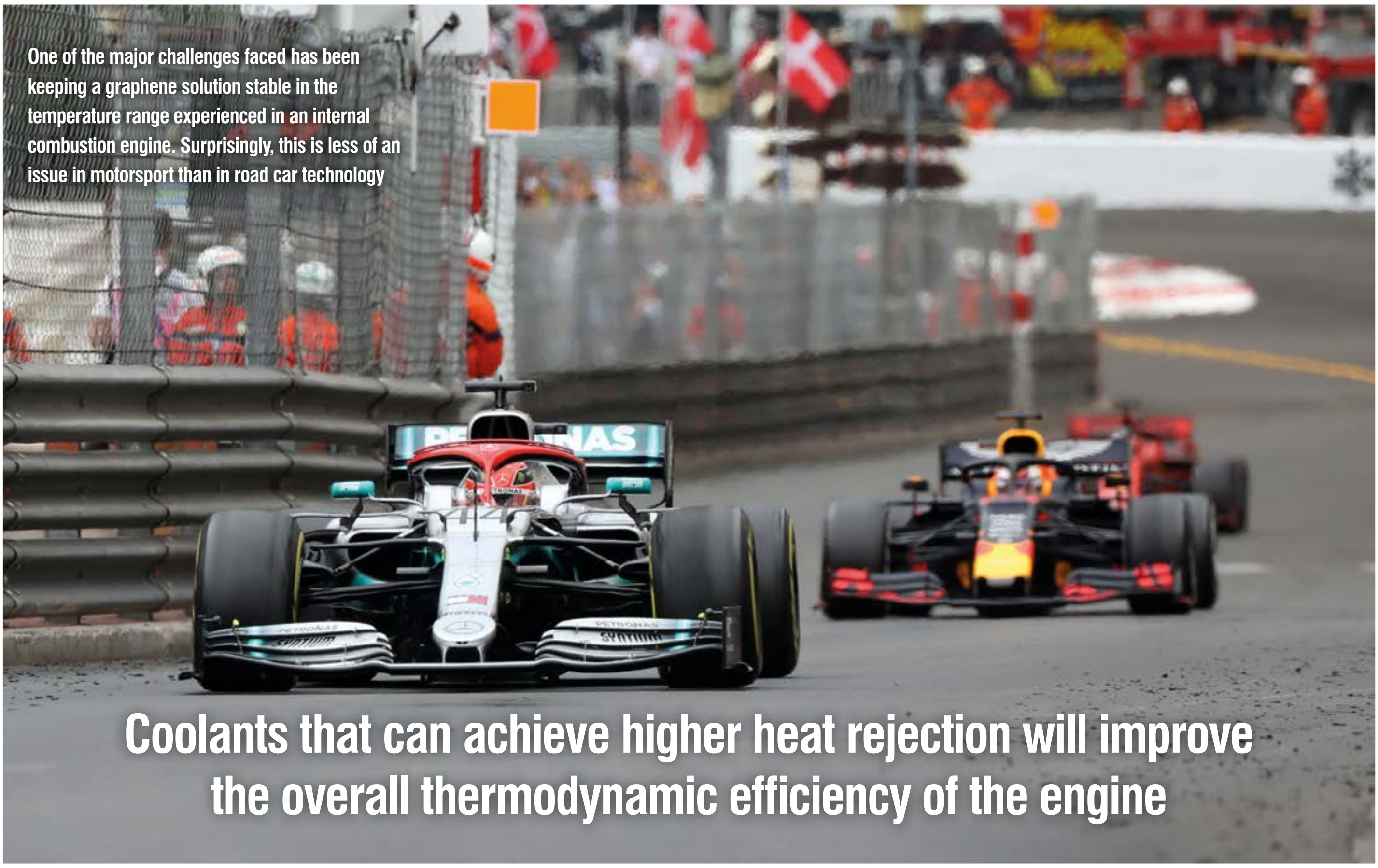
Although F1 engines demand a lot from the coolant, because the engine operates in relatively consistent environmental temperatures, this is actually much easier to design for. Whereas road car engines have to perform in conditions ranging from -35degC to 110degC. Add to this the lifespan of an F1 coolant, which is one race, compared to 50-80,000kms for a road car and you can start to appreciate the technical challenge.

Improving efficiency is the major driver behind every aspect of racecar and road car development today. Extracting the maximum performance out of the minimum amount of fuel, material or time is how motorsport can not only be more sustainable itself, but also help other industries become more sustainable, too. Therefore, coolants that can achieve higher heat rejection will improve the overall thermodynamic efficiency of the engine, and consequently fuel efficiency.

'Most modern engines are already very close to the knock limit but, if you can run your engine hotter, even by a small amount, then the fuel efficiency gains can be quite substantial,' highlights Notley. 'Then there is the benefit of evening out the temperature across a system. For example, hot spots on cylinder liners can lead to a process called nuclear boiling, where gas bubbles form on the surface and the heat cannot be transferred through the gas efficiently. These hot spots lead to fatigue and eventually failure. The ability to reduce or re-use heat more efficiently across the whole system, rather than just a specific area, due to improved thermal conductivity is important.'

Maximising heat rejection doesn't just improve engine and fuel efficiency, though, it also improves the efficiency of the radiators. This means they require less airflow and can therefore be smaller and manoeuvred lower down in the car, offering attendant packaging benefits. This in turn reduces drag and lowers the c of g, improving both aerodynamic efficiency and vehicle handling.

Despite decades of teams optimising the packaging of radiators, the thermal



One of the major challenges faced has been keeping a graphene solution stable in the temperature range experienced in an internal combustion engine. Surprisingly, this is less of an issue in motorsport than in road car technology

Coolants that can achieve higher heat rejection will improve the overall thermodynamic efficiency of the engine

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A side effect of the improved thermal properties of graphene nanoliquids is a reduction in radiator and cooling system size, which is beneficial in motorsport but also far beyond

performance of coolants has always restricted the fundamental design philosophy behind cooling systems. But this is no longer the case with graphene nanofluids. Therefore, this type of cooling technology could revolutionise the way our racecars and road cars look.

Wasted energy

'One of the biggest things that often holds back performance is getting rid of wasted energy in the form of heat,' notes Marc Priestley, director of motorsports and high-performance engineering at Flexegraph. 'So, if you can do that in a much more efficient way, using the properties of graphene particles, the potential is huge. You can easily fast forward and think that this could start to change the design of power units, as well as slim down radiators and bodywork.

'The ongoing effects of this can be far greater than just temperature. They can start to impact aerodynamics and weight. It's fascinating technology but the ongoing potential of this, which we're nowhere near fully realising yet, is huge.'

Another benefit in terms of packaging is the reduced cooling infrastructure that a more thermally efficient coolant enables.

'One Hypercar manufacturer we're working with had an extremely complex cooling system with eight separate cooling loops within the car,' recalls Notley. 'Modern vehicles don't have much available real estate anywhere now, so the car was completely packed. By being able to cool all the different internal combustion and hybrid systems, each having very different temperature ranges, with the one liquid, we were able to have just one cooling loop. This is, of course, very attractive from a cost, manufacturing and packaging perspective.'

To demonstrate the magnitude of performance benefit of these graphene nanofluids, Flexegraph has conducted a whole host of tests. One of which was a back-to-back comparison between an early iteration of graphene nanofluid against a conventional F1 engine coolant.

Power boost

'What the F1 team saw on their dyno testing was a reduction in temperatures of around two degrees,' reveals Notley. 'For them that was quite substantial, because every 0.2degC drop in temperature equated to about 10 additional horsepower they could potentially get out of the engine. If you're talking a full two degrees, that could give a team a major boost in potential engine performance, from a liquid that is relatively low cost to implement into a system.'

Of course, modern racecars don't just have to manage the temperature of the engine, but also batteries, motors and inverters, too. Conventionally, these types of components are cooled in one of two ways:

> **The ongoing effects of this can be far greater than just temperature. They can start to impact aerodynamics and weight**
>
> *Marc Priestley, director of motorsports and high-performance engineering at Flexegraph*

direct or indirect cooling. The former uses fluids in direct contact with the electrical components. So, for batteries for example, the fluid surrounds the individual cells, while for motors the fluid flows around the windings. For this, non-conductive dielectric fluids, which are typically oil-based, are used.

Indirect cooling, on the other hand, utilises cold plates, which are essentially metallic heat sinks that have channels of cooling fluid flowing through them. These can be attached to the cells of the battery and the stator of the motor through thermal adhesives. However, separating the coolant and the components with effectively a metallic layer induces thermal resistance and therefore a loss.


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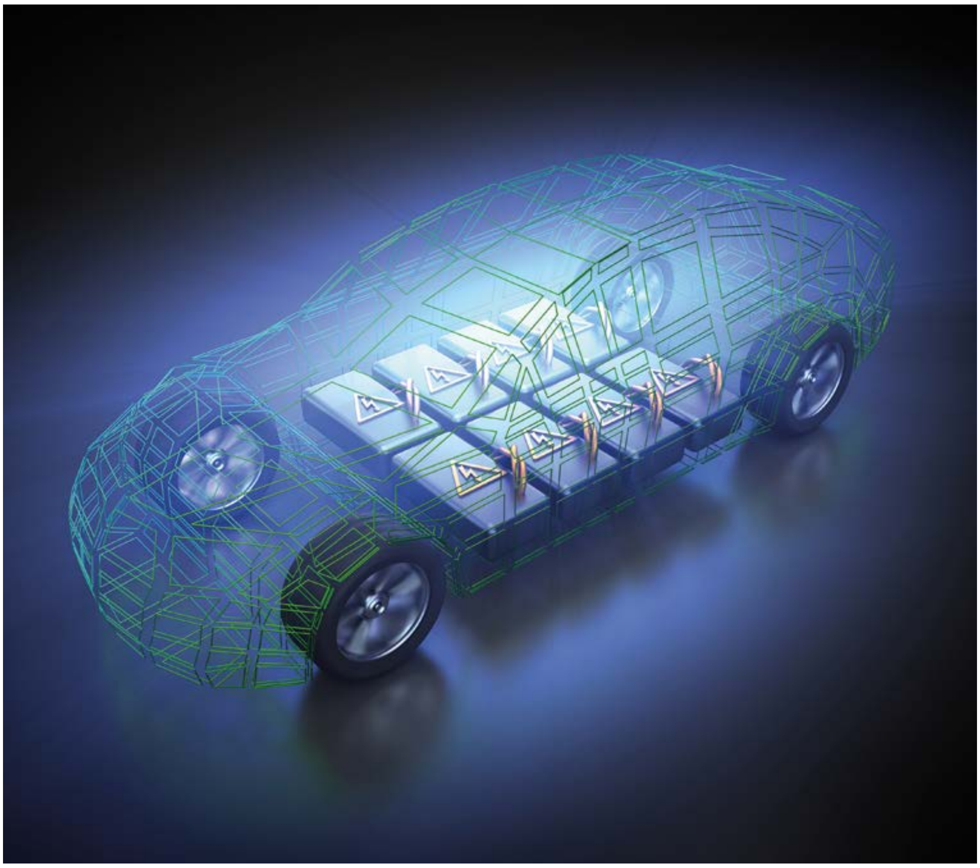
Hybrid and electric car technology requires further cooling loops for the batteries, inverters and electric motors. Graphene nanoliquids can not only help reduce temperature across the whole system but improve battery life, too

Modern rapid prototype techniques can generate cold plates with thin walls, allowing teams to achieve similar levels of heat rejection as direct cooling, but without the weight penalty of flooding a battery or motor with coolant. Reducing the temperature of the battery is vital for safety and performance.

'You can think of an electric vehicle as a giant toaster passing current through a system, and there are losses in that system, which result in heat that needs to be dissipated,' explains Notley. 'The faster you charge or discharge a battery, or the bigger the battery, the more heat it will generate. If the battery experiences high temperatures for an extended period, the number of cycles you get out of it reduces quite substantially.

'But there are other applications for our coolants, too. During fast accelerations, the battery discharges at a phenomenal rate, which then subjects the inverters to huge heat loads, so there are additional opportunities there as well.'

To keep the battery within its optimum temperature range, these coolants can also be used to warm the battery up. 'For us, it's all about rate. You're either pulling heat out of a system more quickly or putting heat in more quickly,' explains Notley.



Improved cooling fluids do not change the amount of energy stored, but better heat transfer uses the energy more efficiently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'Our cooling fluid does not change the amount of energy the liquid can store, but it changes the rate at which heat is transferred across the system. So when you have a cold start, you can bring the temperature of the battery up quicker using our liquid.'

That helps to improve overall efficiency in a battery-based system.

Performance tweaks

After successfully proving the benefits graphene nanofluids can bring to both motorsport and automotive, Flexegraph is now developing techniques to tweak the performance characteristics of the fluid to suit each team's particular set-up.

'A lot of the work we're doing now is finding the perfect viscosity and thermal efficiency level that works for each set-up,' says Priestley. 'One of the big factors everybody wants to be sure of is our fluid won't have a detrimental effect on viscosity. The way graphene works is to trade off viscosity for the heat thermal efficiency. So essentially, the more graphene particles you disperse into a given fluid, the higher the viscosity levels, but also the greater the thermal efficiency.

'For example, each team's pipework and channel sizes within the radiators are slightly different and so the fluid needs a bespoke formulation to suit that particular system. We're at some fairly advanced testing with a couple of different teams now in Formula 1 and IndyCar and we've been able to utilise their amazing testing facilities to give us some really detailed results.

'Getting involved with motorsport has boosted our development as much as it has helped teams get closer to a solution as well. It's a really interesting space,' concludes Notley. 'There has always been this idea that the properties of liquid cooling are static, and there's nothing better than what's been around for the last 100 years. But when people realise we have a liquid that improves heat transfer, minds are blown. Whenever we speak to someone new, we find another problem that graphene nanofluids can help to solve. A lot of the engineers we work with say they've never heard of this technology before and initially don't believe us. But then when they do the tests and see the capabilities of our coolants, as well as the benefits this brings to their systems, they become believers.'

The more graphene particles you disperse into a given fluid, the higher the viscosity levels, but the greater the thermal efficiency

Marc Priestley

Other applications

Cooling engines and hybrid components is not the only application of graphene nanofluids.

'We cut across three major industry verticals – automotive, computing and power generation,' says Flexegraph's Shannon Notley. 'That demonstrates the breadth of this sort of technology.'

The company has already developed coolants that manage the temperatures within the charging infrastructure for hybrid and electric trucks and buses. By utilising the higher thermal conductivity of graphene, not only have the charging cables reduced dramatically in size and weight, but the charge time has also decreased, so vehicles can be back on the road quicker.

Another application is computer cooling. Flexegraph's liquid cooling technology is already being used to manage the thermal output of high-performance computers and large data centres.

Interestingly, as well as the need to be kept cool, motorsport and computing share another requirement, the use of dyes.

'There is only one colour you'll get with graphene coolants, and that's black. But, interestingly, a talking point for many customers has been the colour,' reveals Notley. 'They want the coolant to be bright yellow or green so, if there's a leak, it's immediately visible and the engineers can tell exactly what fluid has leaked and where it has come from.

'Some of our PC cooling customers have also requested we change the colour for their high-spec gaming machines. Often these now have transparent cases with liquid cooling loops around the CPUs. It's essentially a hot rod for computers, and people want to have brightly coloured dyes circulating around their consoles. It's an interesting additional challenge we never thought we'd have to consider.'

'Hot rod' cooling for your games console?

Graphene coolants are already in use in electric truck and bus infrastructures, reducing cost and down time and therefore improving productivity

Motorsport and computing share another requirement, the use of dyes

Powder keg

Additive manufacturing is a hot topic. *Racecar* looks at the pros and cons of the various current methods and their relevance to motorsport

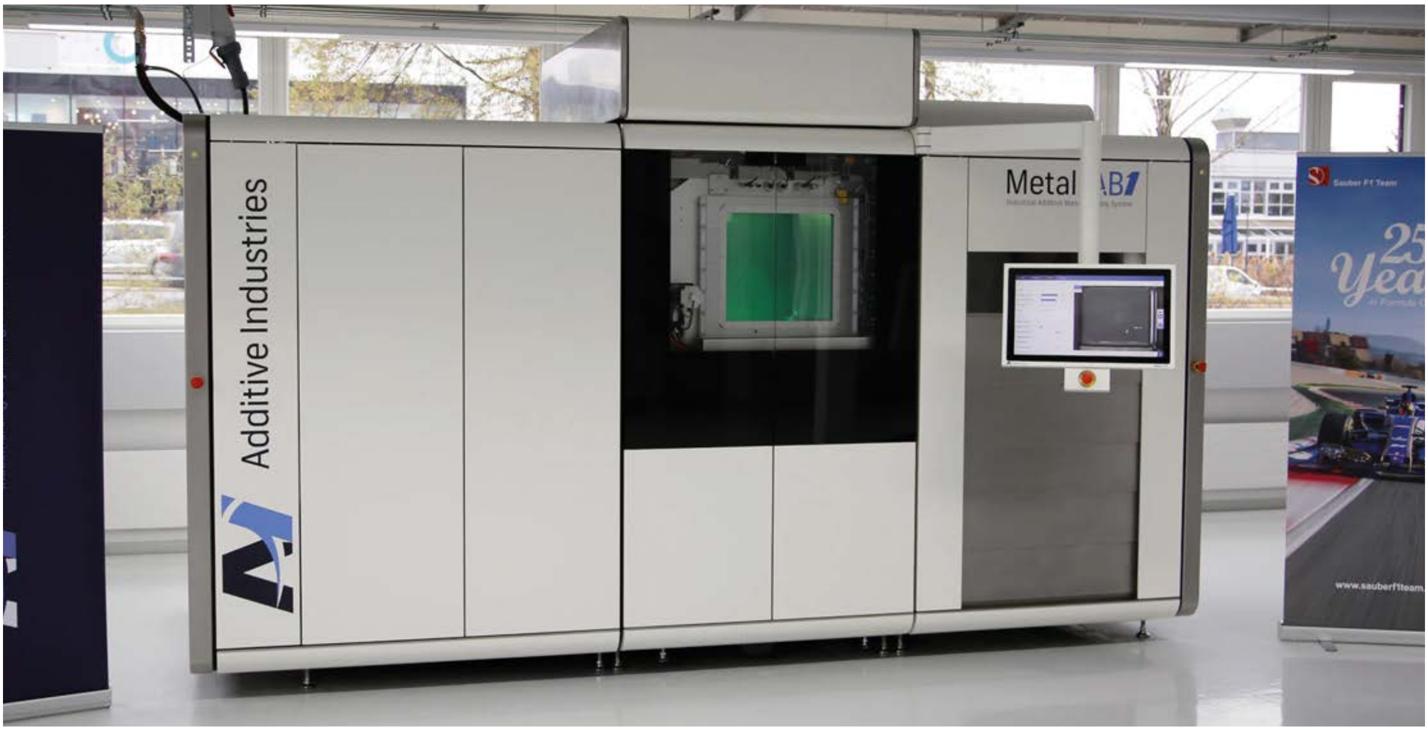
By LAWRENCE BUTCHER

The big draw of AM is the ability to create geometries that would be impossible to achieve using subtractive machining or casting

This heat exchanger manufactured by Conflux Technology is a perfect example of how the geometric freedom offered by AM can be exploited to optimise efficiency

Additive manufacturing (AM) technology has, over the past decade, established itself as almost indispensable in the motorsport industry. As the mechanical properties of components produced using AM have advanced, so have the potential uses, and their adoption in applications where previously only machined or cast parts would be considered suitable.

The scope of the technology can at times be bewildering, ranging from what one could term 'hobbyist' 3D printers through to industrial scale, multi-process machines capable of producing high-strength metal parts, fully heat treated and almost ready to fit. As with any manufacturing technology, there are limits to what can and can't be achieved, but these are constantly being eroded as machinery manufacturers' process engineers advance their knowledge.



F1 team, Alfa Romeo Sauber, has been using AM processes for over a decade now and has extended its technology partnership wth Additive Industries through to 2022

There is also an element of engineering design theory having to play catch up with new techniques. The entire concept of Design for AM (DfAM) needs to be adopted to fully realise the benefits it can bring. The ability to produce previously unmachinable forms means engineers are having to re-think their design approaches, which have been cemented over years of producing parts within the constraints of traditional subtractive machining or casting processes.

In many ways, this shift is similar to that which occurred when five-axis machine tools became commonplace.

Motorsport applications

For the purposes of this article, we will concentrate on the AM process most commonly employed for functional component production racing (see box out on p71 for a description of the various current AM technologies), powder bed fusion, both of polymers and metals.

Polymer processes use lasers for material heating, while metals can be melted with either lasers or electron beams

The terminology of even just powder bed fusion methods can be confusing, with 'brand names' representing what are effectively the same technologies. SLS (selective laser sintering) is generally used to refer to the manufacture of polymer parts, and direct metal laser sintering (DMLS) / direct metal laser melting (DMLM) refers to, as the name suggests, metal parts.

Polymer processes use lasers for material heating, while metals can be melted with either lasers or electron beams.

Polymer processes

Looking first at polymers, there are a plethora of materials that can be deployed in racing, with some larger outfits even now researching their own blends. Sauber, for example, which has utilised SLS technology for over a decade, has developed a material based on Nylon 12 that it employs for the production of parts such as brake and cooling ducts. Called HiPAC, it is reinforced with carbon fibres giving it a tensile strength of 85MPa and, importantly, is temperature stable up to 170degC. If one looks at the Alfa Romeo Sauber team's pit lane equipment, it is easy to spot various adapters for leaf blowers used for brake and powertrain cooling produced using this material.

Another long time and prolific producer of polymer-based materials is Italian firm CRP Technology, which offers a range of reinforced powders. All falling under the Windform brand, these are tailored for specific demands. For example, its FX Black material is engineered to endure bending and torsional loads, and exhibits good impact resistance – similar to polypropylene.

There is an ever-increasing range of metal types that can be processed, covering everything from gold to titanium and steel

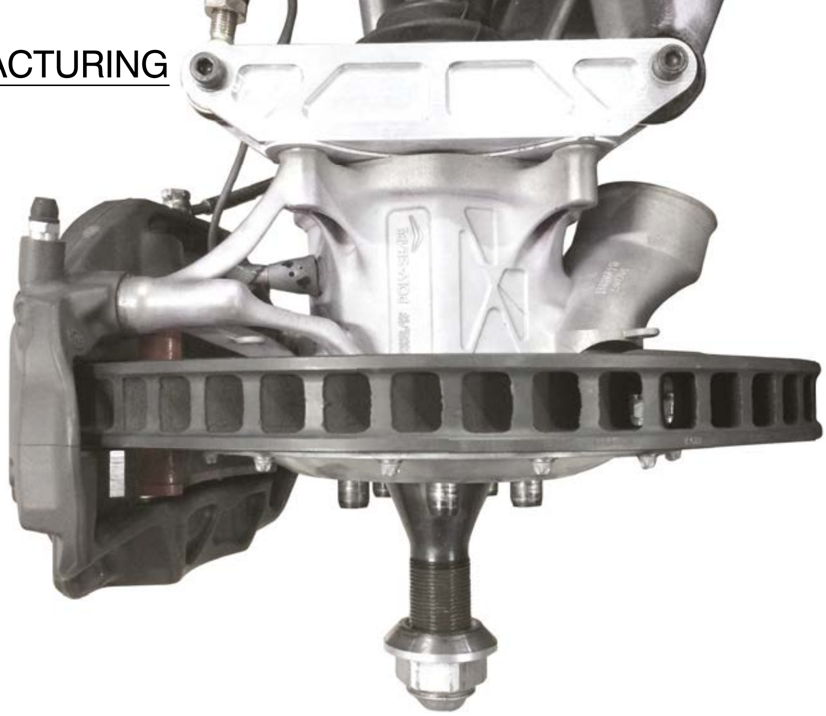
Meanwhile, its XT 2.0 material features carbon reinforcement and can be used as a substitute for traditional carbon fibre composites in some applications.

Metal processes

Moving to metals is where things get really interesting, and it would be fair to say it's where the most exciting current developments are taking place. There is an ever-increasing range of metal types that can be processed, covering everything from gold to titanium and steel.

For racing applications, the materials of greatest interest are aluminium and titanium alloys. With aluminium, most casting grades are available in powder form, such as AlSi10Mg and AlSi12MG, though higher performance alloys have also come on the market. One such material is Scalmalloy, developed by specialist AP Works, which sees aluminium alloyed with scandium and magnesium, giving finished properties similar to 7075 wrought alloy.

The AM components on this page made by French firm Polyshape, including a hydraulic block (below) and high-load parts such as the suspension upright (right and below right), show just how advanced additive manufacturing technology now is



Scalmalloy has an impressive tensile strength of 520 MPa (compared with AlSi10Mg, at 350MPa) which is about half that of Ti6Al4V titanium, but combines that with a density the same as AlSi10Mg (2.6g/cm3). In addition, its microstructure remains stable up to 250degC, making it suitable for high-temperature applications.

When it comes to titanium, Ti6Al4V and Ti6Al7Nb are the most commonly used grades for AM and have been employed in a variety of racing components, from roll hoop structures to suspension parts. Sauber, for example, has been working on functional suspension rockers, while French firm Polyshape has produced suspension uprights, including those used by Romain Dumas in his Pikes Peak cars.

Another important AM-suitable metal is Inconel, and a glance at any current Formula 1 power unit will reveal exhaust components produced in this material. Prior to the regulation clamp down on blown exhaust systems, many teams used AM for the production of tailpipes and other elements to create geometrically complex forms that would be impossible to fabricate.

There have also been recent developments in the area of binder jetting technology, rather than powder bed systems, to facilitate the mixing of different material types within a single AM part.

Most notably, the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) in Germany has pioneered a process that allows for up to four different material types to be mixed in a single part, with powdered metal or ceramic being deposited in build layers simultaneously, along with a thermoplastic binder material.

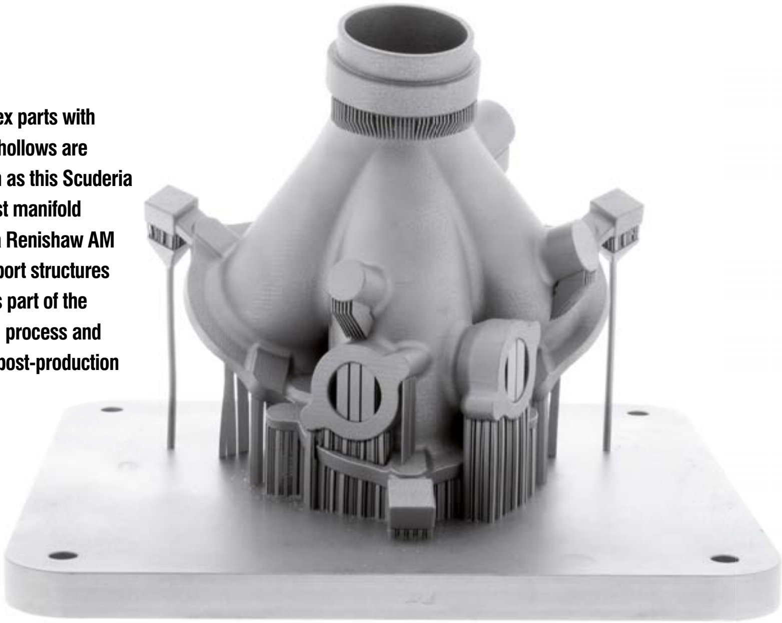
Post-production, the parts are heated in an oven to sinter the materials together. In this way the properties of parts can be precisely tailored, for example to maximise thermal or electrical conductivity in certain areas, or enhance wear resistance (the process can also deposit carbide).

Process control

When it comes to creating reliable parts using AM, be they metal or polymer, process control is everything. While this is the case for any material manufacturing process, legacy technologies have decades, if not hundreds of years, of accumulated knowledge behind them. Even then, porous or poorly consolidated castings are not uncommon.

For AM processes, the learning curve is still steep. Melting or sintering metals needs to take place in an inert atmosphere. However, some oxygen will always remain, which influences the properties of a finished part. Additionally, much like casting, there will always be a degree of shrinkage or distortion to a part, either during manufacture or post-processing during such as heat treatment.

There have been recent developments in the area of binder jetting technology… to facilitate the mixing of different material types within a single AM part



Where complex parts with overhangs or hollows are required, such as this Scuderia Ferrari exhaust manifold produced on a Renishaw AM machine, support structures are created as part of the Design for AM process and machined off post-production

This bewildering array of variables makes correct characterisation and validation of both materials and processes vital for reliability

AM front wing elements and other components made by the technical partnership between EOS and Williams F1

AM technology categories

According to the American Society for Testing and Materials (ASTM), there are seven distinct categories of additive manufacturing processes. Not all of these are relevant to motorsport applications, but it is wise to at least acknowledge their existence.

Vat photopolymerization
This process uses a vat of photopolymer resin, which is cured in layers using UV light to form a net shape. This was one of the first technologies utilised in motorsport, with teams using SLA (Stereolithography) to produce wind tunnel parts. Most teams still use such machines as they are capable of producing detailed parts, relatively quickly, sometimes with useful properties such as translucence.

Material jetting
Much like an inkjet printer, material is deposited layer by layer either as a jet, or in droplet form. Each build layer is then cured using UV light. One benefit of this technique is that it can be used to produce multi-coloured parts, which can be useful for prototyping applications.

Binder jetting
This method involves two materials, normally a powder base and a liquid binder, with the binder deposited on the powder layer by layer to form an object. Not as commonly used, particularly in the motorsport industry, but current developments in this technology may make it more relevant.

Material extrusion
Probably the most well-known form of additive manufacturing. Commonly referred to as Fused Deposition Modelling (though this is a trademark of manufacturer, Stratasys), a filament of material is drawn through a heated nozzle and deposited on a print bed layer by layer, with the build platform moving down to allow each new layer to be formed. The filament is almost always polymer-based, but the latest developments include fibre or metal-reinforced materials, as well as those with rubber-like properties.

Though having found the limelight as hobby machines, FDM has great potential, particularly for producing prototype parts or even lightly loaded functional components.

Powder bed fusion
This category covers a host of different methods of additive manufacturing, all of which rely on the heating or melting of a powder material stock. The material can be polymer-based or metal and it's probably the area with the most ongoing development. Not least in the production of metal parts with sufficient properties to be used in highly loaded applications.

Sheet lamination
Quite a specialist process this one that relies on the ultrasonic welding together of thin sheets of material.

Directed energy deposition
Finally, another specialist process, but one which does have a role to play, for example, in the restoration of historic motorsport components. An energy source, such as a laser or electron beam, is used to melt material that is either jetted (in powder form) or fed as a wire onto an existing surface. One of the most common uses of this process is the repair of shafts, and it can be a cost-effective means of reviving high value components that are subject to wear or damage.

There are also a host of other process parameters that affect the final part: the power of the laser; scan speed; powder distribution; individual particle size; layer thickness, to name just a few.

This bewildering array of variables makes correct characterisation and validation of both materials and processes vital for reliability. If one adds in the potential for hidden internal features, which add further complexity to post-production part inspection, the challenge of validating the performance of AM parts becomes clear.

Take, for example, the development of AM heat exchangers, which are currently being deployed by some Formula 1 teams (see opening image in this feature). The benefits these bring, both for packaging and efficiency, are considerable. Not only can they be constructed in any form, meaning they can be packaged in places traditional exchangers cannot, they are more efficient thanks to the ability to precisely control the internal wall geometry of the passageways, in order to influence factors such as turbulence and boundary layer formation.

However, their very effectiveness relies on extremely thin wall thicknesses, at the limits of the resolution available from the highest-end AM machines. Any porosity is clearly unacceptable. Ensuring these stringent demands are met requires an in-depth understanding of every stage of the manufacturing process, and the effect any variations have on the material structure.

Validating whether these demands are being met involves the use of both destructive and non-destructive inspection methods. Parts will be checked using x-ray micro-computed tomography (microCT), which allows for inspection of internal structures at a microscopic level, even down to being able to assess the microstructure of the metal at different points within a part.

Design for AM

Extracting the potential of AM starts well before any material processing takes place and relies on the manufacturing process being considered from the very start of the design process, the aforementioned DfAM.

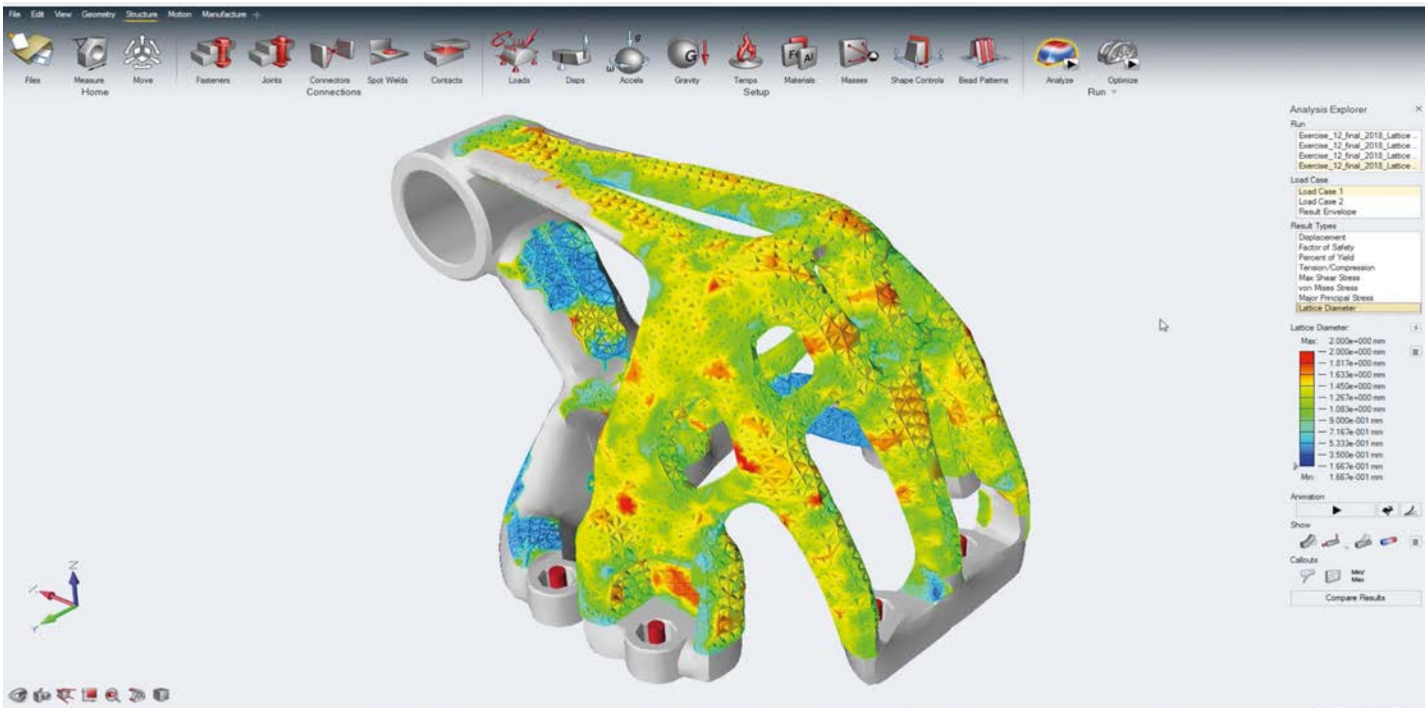
One example of the way AM changes the very philosophy of design is the lack of consideration needed for tool access or part fixturing, which is ever present when conceiving parts to be machined. However, there are a host of new factors that must be considered. Key amongst these are the potential for residual stress build up in parts, a part's orientation within the build chamber, any support structures needed and optimisation of a part's topology.

Addressing residual stress first, this is a result of the rapid heating and cooling of a part as the material is melted. If stresses get too high, or are concentrated in one area, problems such as warping starts to rear its head. Various steps can be taken in the design process to reduce the chances of distortion: avoiding large continuous surfaces, where material is melted in an uninterrupted line, and the addition of a substantial base plate that can be machined off post-production help keep part integrity. Additionally, the pattern the laser traces over the powder can be altered from layer to layer, for example using a cross hatch system, to help even out stresses within a part.

The orientation of a part and the need for support structures are interlinked. When dealing with a powdered bed of material, large overhangs cannot be produced without either compromising on surface finish or, in extreme cases, part integrity. Simply changing the way a part is orientated in the build chamber can remove the need for overhangs. Imagine the letter 'o' being printed, if done vertically, there are large overhangs, if printed flat on the bed, there are none.

In some cases, overhanging features are unavoidable, in which case support structures are employed. These are additional printed sections that will be removed via machining (or, in some polymer-based processes, can be dissolved away) that support overhangs. To reduce part production time, both during printing and post-processing, and to optimise material usage, it is desirable to keep their use to a minimum. To this end, most software with dedicated Design for AM functionality will have the ability to automatically generate support structures in the CAD data, with various parameters that can be varied to optimise their placement.

Extracting the potential of AM starts well before any material processing takes place and relies on the manufacturing process being considered from the very start



CAD file showing how a part is optimised prior to manufacture by AM, particularly in regard to stress build up during construction. Image courtesy Altair

There is also research underway into AM processes that can incorporate electrical circuits into parts, opening up a host of possibilities for integrated functionality


Proof positive of how far additive manufacturing has come, Porsche is currently testing AM pistons made by Mahle

Careful consideration of a parts features can also reduce the need for support structures. For example, if a hole doesn't need to be round, other geometries can be used that are better at self-supporting, such as teardrops or diamonds.

Optimisation

Beyond the design constraints around manufacturability, the big draw of AM is the ability to create geometries that would be impossible to achieve using subtractive machining or casting. This capability opens the door to a very high level of topological optimisation (TO) of parts, a process that predates AM but complements it well.

TO is actually a subset of an approach known as generative design, whereby a design, or number of design options, is outputted by dedicated software, based on a variety of input constraints. Instead of an engineer coming up with an initial concept for a part, and then refining it to ensure it meets the required load cases, mass targets etc, with a generative design, one moves back a step, simply providing the software with the key constraints.

In the case of a suspension upright, for example, these constraints might include the wishbone and brake mountings, the load cases, safety factors, material (or range of materials) selection, stiffness and available manufacturing techniques. The generative design program will then take all these constraints and output a variety of different designs, from which the engineer can choose a preferred option.

One solution might provide the ultimate in stiffness-to-weight ratio, but with a lower safety factor than might be ideal, or it may take much longer to manufacture than a design that is slightly less optimal from a functional perspective, but can be made in half the time. Naturally, there is a catch. Such systems are still in their genesis and a degree of engineering caution still needs to be applied to the results they generate.

Generative design incorporates TO, which is where software simulation is able to pare down the design of a part to the point where it retains only the material needed to fulfil its function. The result being the very organic structures that are increasingly commonplace on racing components (AP Racing's RadiCal brake calipers were one of the first mainstream manifestations of this approach). In the past, some of the more far-out geometries that TO produce simply could not be machined, but AM makes them possible. However, the aforementioned constraints of the AM process still need to be taken into consideration.

Research into AM capability continues apace, with new materials, processes and machinery undergoing constant testing

Future potential

The capabilities of AM continue to advance at a considerable rate, thanks to both improvements in machinery and engineering understanding of materials and processes. One only need look at projects such as Mahle's production of AM pistons, currently undergoing testing with Porsche (it is also rumoured that F1 engine manufacturers have been experimenting within printed pistons). Such an application would have seemed impossible just a few years ago.

Elsewhere, there is also research underway into AM processes that can incorporate electrical circuits into parts, opening up a host of possibilities for integrated functionality within components. Ultimately, the true potential of Additive Manufacturing is only just becoming apparent, and its use will surely only increase as understanding of its benefits grows, and cost are reduced.

The art of knowledge

Or how to ask the right questions in racecar engineering

By DANNY NOWLAN

Firstly, you must get to know your racecar, backwards, forwards and side to side. This is where simulation helps, as the process forces you to understand how your car behaves

One of the biggest bugbears I have with motorsport engineering is when people ask what is the optimum camber setting? Or what is the magic ride height relationship through a corner? Or is there a single metric to use for the lateral load transfer distribution through a corner?

To me, these questions not just miss the point, but also illustrate motor racing's perpetual, and destructive, obsession with quick solutions. In recent years, this has been further amplified with engineering education moving away from first principles and seemingly becoming more interested in breeding a generation of computer-aided engineering jockeys.

The key to answering these questions is to know how to ask the right question in the first place. This is what we are going to be exploring in this article.

Make no mistake, the art of asking the right question doesn't just form the basis of sound motorsport engineering, but is a critical life lesson. There is an old saying, 'Give a man a fish and you feed him for a day. Teach him how to fish and you feed him for a lifetime.' In other words, once you know the underlying principles, once you know how something *genuinely* works, everything else comes out in the wash and questions such as those I listed at the beginning are a by-product.

In the motorsport engineering sense, in order to ask appropriate questions, you must know your car backwards. For me, this is the pay-off from using simulation. It's not the simulated data at the end, it's not the fact we changed this spring or that damper and achieved a certain result. The benefit is that if you are using something like ChassisSim, the very process of simulation forces you to understand your car.

It's something I find myself very torn on. About 80-90 per cent of the motorsport engineering fraternity either can't do this, or don't want to do it, or think it's beyond them. To that portion of the population I say, trust me, it's worth it.

To understand a car – in order to ask the right questions – it all boils down to tyres, suspension geometry and aero.

To understand a car – and then in order to ask the right questions – it all boils down to tyres, suspension geometry and aero

In a race engineering sense, from these three things everything else flows.

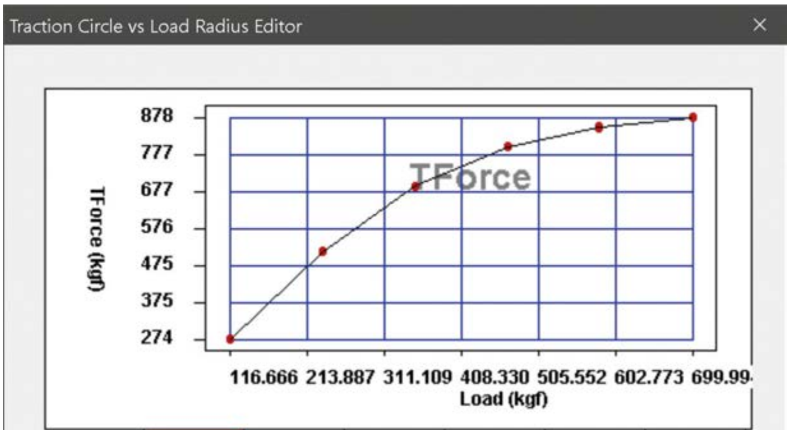
Tyres first

So let's first talk tyres because, to quote the late and great Mark Donohue, the four contact patches of the tyres is what separates you from St. Peter.

In order to understand the tyre, it boils down to three graphs. The first is the Traction Circle (TC) radius vs vertical tyre load. This is illustrated in **Figure 1**.

This represents the heart and soul of racecar performance because everything

Figure 1: Traction Circle radius vs tyre load



Load	116.666	233.331	349.997	466.663	583.329	699.994
TForce	273.975	512.495	689.500	797.987	850.263	877.961

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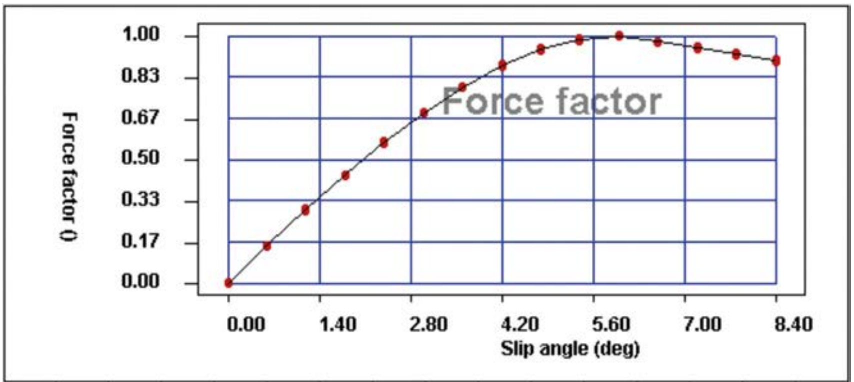
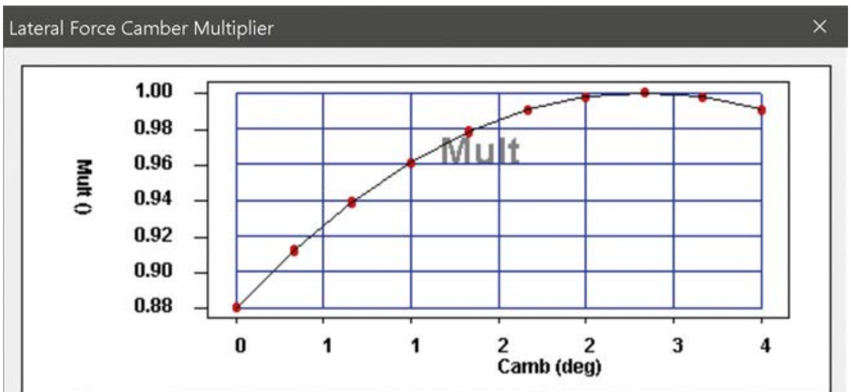
Figure 2: Normalised slip curve



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

Figure 3: Tyre lateral camber sensitivity



Camb	0.00	0.39	0.78	1.17	1.56	1.94	2.33	2.72	3.11	3.50
Mult	0.88	0.91	0.94	0.96	0.98	0.99	1.00	1.00	1.00	0.99

flows downstream from this. Without a shadow of a doubt, the most significant aspect of it is the delta between the maximum tyre load seen on track and the load at which the tyre produces its peak TC radius. The bigger the delta between them is a direct measure of how stiff you run the car. For example, if that delta is under 50 per cent, this tells you to run stiff springs / dampers and low roll centres because you need to work the tyre. If it's 20-30 per cent, this dictates high roll centres and soft springs because you need to look after the tyre.

A trap for young players here is that most tyre test rigs will over predict the TC radius load peak. You get this model from actual data and the techniques for this I have spoken at length about before.

Also, a quick note about thermal effects and the TC radius vs load characteristic. To ignore thermal effects on this relationship is a bit like ignoring gravity. You can't. That being said, something like this with an Excel force balance sheet can get you into the ballpark very quickly.

The other big driver of this will be the internal and surface temperature of the tyre. As a rough percentage, it's about 60 per cent internal, 40 per cent surface, but that is only a rough rule of thumb.

Normalised force

The next curve to understand is the normalised tyre force vs slip angle / slip ratio curve. What I mean by normalised force is tyre force divided by the maximum TC radius value. Plot this and you get a curve that looks like **Figure 2**.

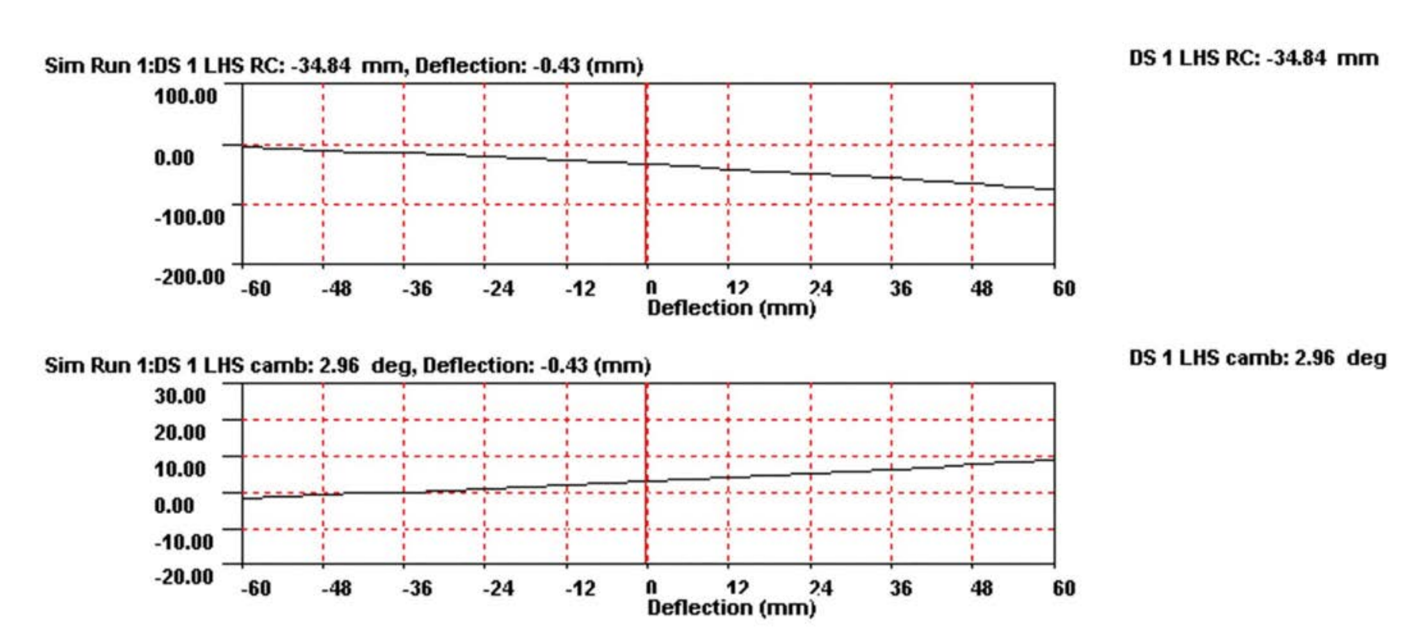
The impact this curve has on car handling is massive, and it all revolves around the peak slip angle, the slope of this curve and what it does when you exceed the maximum slip angle and go post-stall.

The smaller the slip angle and the steeper the slope means the car will be very sensitive to steer input. In aerospace parlance, this is often termed control power. How this curve drops off post-stall tells you a lot about how forgiving (or not) the car is when it's on the edge of its performance envelope. For example, if that drop off is, say, a force factor of 0.95, the car will be quite forgiving post-stall. I spoke about this at length in my article about quantifying Rally dynamics. Conversely, when you start dropping to a force factor of 0.8, you are dealing with something very unforgiving.

The last piece of the puzzle is how tyre force varies with camber. A rough guide from some F3 class tyres validated from race data is shown in **Figure 3**.

While camber sensitivity is not to be ignored, it's the lowest order effect of what we have discussed. Note in **Figure 3** the

Figure 4: A plot of roll centre height and camber vs roll deflection



max variation is a force factor of 0.88, with a peak of 2.7 to three degrees of negative camber. Where camber variation makes its presence felt is when you have a big tyre. The first generation A1GP car was a classic case in point of this.

So how do we tie this all together mathematically? As shown in **Equation 1**.

$$F_y = C(\alpha)\cdot C(\partial_{camb})\cdot(F_{m1}+F_{m2}) \quad (1)$$

Here we have,

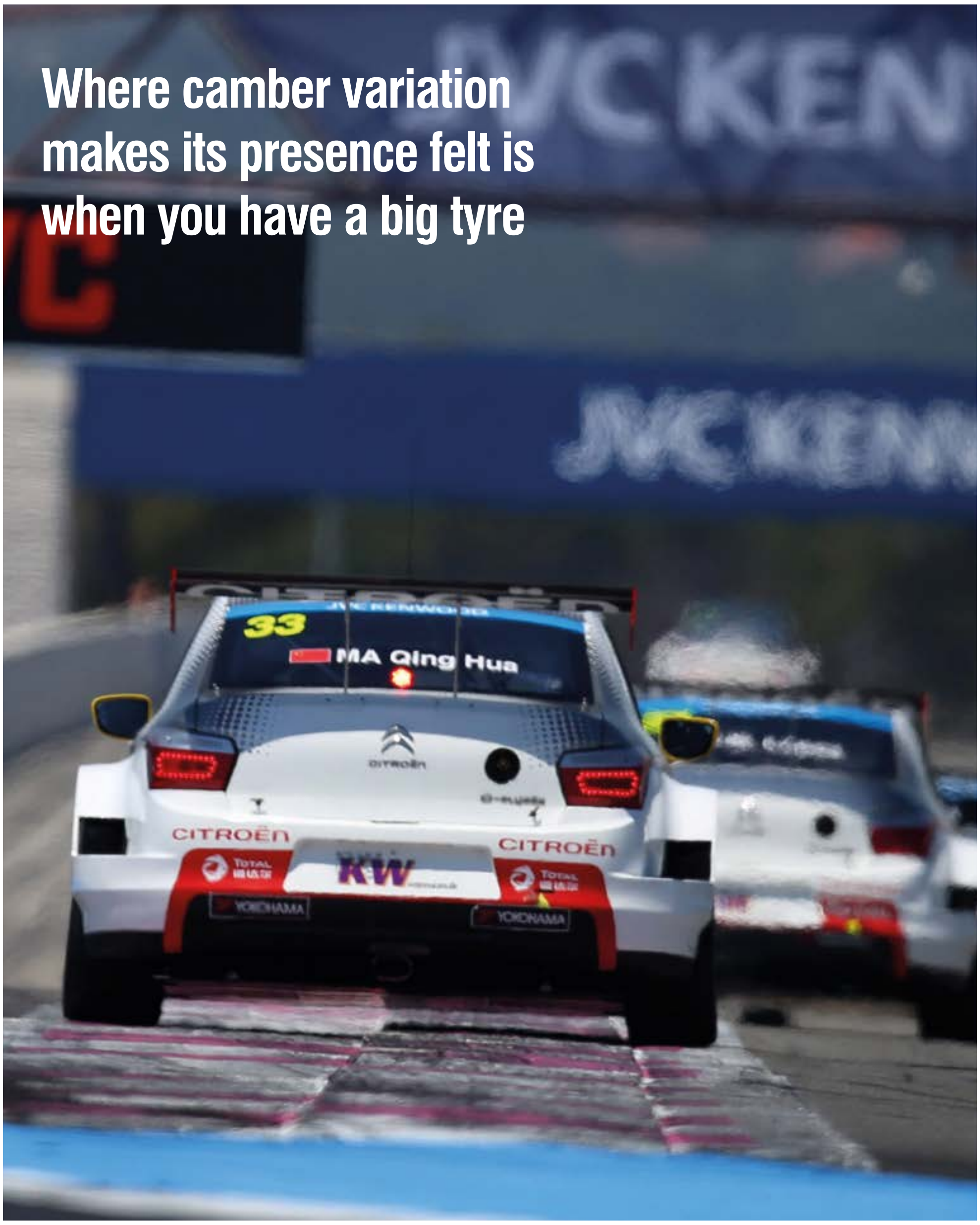
- F_y = axle lateral force (N)
- $C(\alpha)$ = normalised function of force vs slip angle
- $C(\partial_{camb})$ = normalised function of force vs camber
- F_{m1} = Traction Circle radius of the front left (N)
- F_{m2} = Traction Circle radius of the front right (N)

While this is a simplification, it will put you in the ballpark. So, for example, to answer the question on control power, you take the derivative of **Equation 1** with regards to slip angle. The camber relationship and **Figure 1** dictates the F_{m1} and F_{m2} terms.

Suspension geometry

The next step is to understand the suspension geometry of your car. The ins and outs of which I have discussed in my book, *The Dynamics of the Race Car*, and in previous *RE* articles. However, if you want to distil this down into a picture of just what you need to know, **Figure 4** nails it.

This tells you how the roll centre is varying. It also tells you what the camber is doing. All you then need to do is cross reference this with what we discussed in **Figures 1** and **3** and it starts to fill in the blanks. You perform the same analysis for pitch centre as well, albeit looking at movement in pitch.



Secondly, you must understand the suspension geometry of your racecar. There is no one-size-fits-all for this

Once you know your map it starts to answer some key questions

The other thing to pay attention to is bump steer. If we cross reference back to **Figure 2**, this tells you exactly where you need to go with that. If the peak slip angle is very small, it tells you immediately to minimise this. If you are stuck with a production car and tyres that have low to moderate slip angles, you can combine the two to tell you what toes you need to be running at. This is why the detail matters, because it tells you where to go with the set-up, rather than guessing.

Aerodynamics

The last piece of the puzzle is aerodynamics. It continues to astound me on a daily basis why most practicing race and performance engineers don't learn how to calculate this from race data. Information like that presented in **Figure 5** is critical to understanding racecar performance.

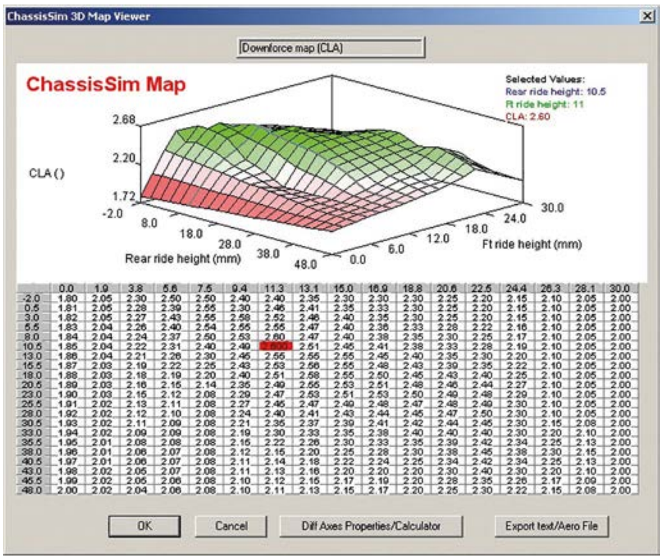
The map shown was a critical piece that helped Team China punch well above its weight in the first generation A1GP car. Once you know what this map looks like, it starts to answer some key questions about ride height sensitivities, where you need to run them and what you have to be prepared to put up with.

Why bother doing all this? Because once you know what the tyres, geometry and aero are doing, all those questions about where to set cambers, ride height and springs all pop out in the wash. Armed with this knowledge, you can now put together plots of lateral force and stability index vs lateral load transfer distribution, as illustrated in **Figures 6** and **7**.

The whys and wherefores of this I have explained in previous articles, but the end result is you are no longer guessing at a set-up, you have a firm understanding of where the numbers come from.

In closing then, the key to racecar performance is asking the right questions. Remembering the fish saying at the beginning, next time you want to know what the optimum camber range is for a car, or what the perfect range of ride height is, or what spring you should be running, ask first what the tyres are doing, what does the suspension geometry look like and what is happening with the aero. Ask *those* questions and the answers to the other questions will take care of themselves.

Figure 5: CLA aeromap of front vs rear ride height for the first generation A1GP car



This is why the detail matters, because it tells you where to go with the set-up, rather than guessing

Figure 6: Total lateral force vs lateral load transfer distribution

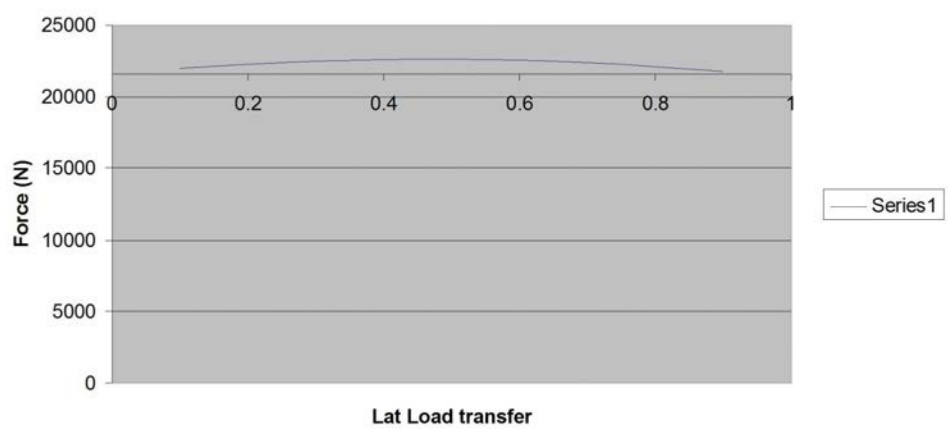
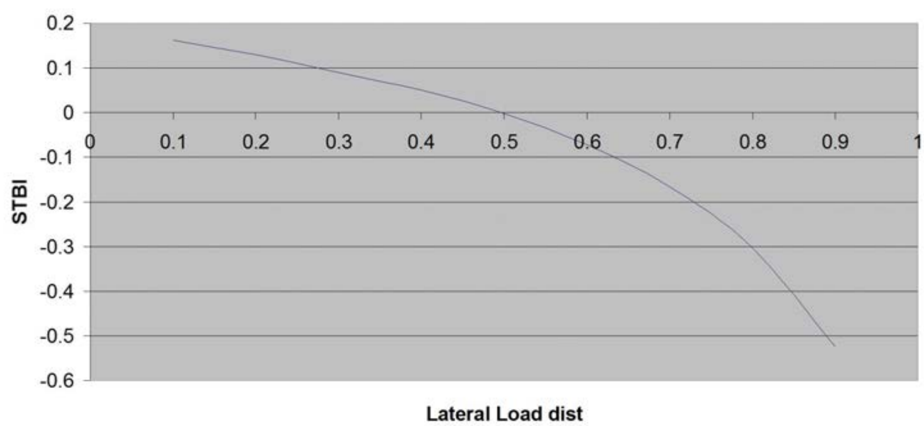
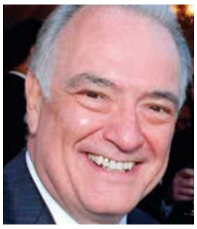


Figure 7: Stability index vs lateral load transfer





Good, but tough, times ahead

A golden opportunity to promote the value of the motorsport industry

Strange times everywhere, so don't worry if you feel confused, you're not alone!

After six months of restricted access, we're just beginning to open up. Despite fears of a second wave of the virus, we need to get business moving again. Using MIA links, I talk with a wide range of business people from motorsport and high-performance engineering around the world, and things are heading in the right direction.

Motorsport entertainment is moving forward due, in part, to leadership from Formula 1, NASCAR and series who've accepted there being no live audience. This is welcome news for competitors, sponsors and suppliers, but without major commercial impact as yet.

The return of live audiences and amateur motorsport will take time, so much of the business value of the 2020 commercial and sporting year will have slipped by. The best the supply chain can plan for is an early start to the 2021 season later this year and early next, with reduced budgets.

Great show

We face a new paradigm in the business cycle of motorsport entertainment. Series and teams have found they can put on a great show using less track time, days away from home and testing, thereby reducing many costs. TV audiences still enjoy the racing, and so will live fans. F1 demonstrates how they can reduce the time to deliver a race spectacle at one track, and then again the following weekend.

NASCAR is running exciting races on a shorter visit programme to its tracks, again reducing travel, accommodation costs and track time. In 2021, expect other series to adopt these measures as they don't impact on the audience or sponsors. In time, teams and competitors will benefit, too. Investment in top-class engineering supplies will continue as the need to win, by spending on the best product to secure a winning formula, will remain an essential part of the process.

Good news for innovative, quick-to-react suppliers will be significant new spending on energy-efficient motorsport as automotive moves to zero emission in 15 years' time.

A variety of solutions – fuel cells, hydrogen, synthetic or biofuels, and ever more efficient battery power, will appear on track in the near future. R&D spending by the automotive industry in these areas will be enormous, and motorsport will take a share as new series will be needed to demonstrate these solutions.

Just as Formula E enjoyed success, so will synthetic-fuelled GT, electric karting and hydrogen hybrids be on track soon.

The future is not full-electric, says the MIA, but right now it is a main focus and series like Formula E, with its BMW i8 safety car, illustrate the close relationship between motorsport and production

By 2035, governments propose that only fully-electric cars will be allowed for sale. The MIA does not accept this, and recently joined with the IMechE to tell the UK government so. We suggest that in addition to aiming for fully-electric power, they would be wise to consider hybrid power.

As our knowledge increases of the political, social and technological difficulties 'battery power' faces, any of which could destabilise the proposed timetable and solution, we encourage a more prudent view be taken by investigating and demonstrating other potential forms of power. This approach would prompt not only an exciting period of R&D investment, but the battle between various energy-efficient solutions on racetracks around the world would provide knowledge to automotive OEMs and attract public interest.

You can read our response here https://the-mia.com/news/521284. Let us know your views.

The UK government clearly recognises the future value of Motorsport Valley to a newly independent UK from January next year. The outstanding efforts, speed and agility of Formula 1 teams and their suppliers to meet the engineering demands of the respirator challenge alerted the government to the wider value of our industry. You can help *your* business and build on this important momentum by writing a short, upbeat message to your MP explaining what you do in motorsport. They need to hear how valuable it is for the UK to build on this world-class strength, as we become independent and leave Brexit behind us.

Your MP will want to be seen to support 'winners', and so will pass your comments to the appropriate minister. In a post-Brexit Britain, the government needs winning, innovative SMEs who export, and that defines our motorsport sector.

Bang the drum

An independent UK will see substantial investment funding from government, much of which will be focused on automotive innovation and technology, our motorsport heritage. We must step up and bang the drum loudly to MPs and ministers alike, reminding them we've been energy-efficiency specialists since racing started over 100 years ago and motorsport is a unique, vital part of UK automotive's future.

I suggest you take time to carefully analyse and understand which of your company's capabilities are most competitive and profitable, as well as your speed, agility and competitive success, of course. As you move into 2021, you will need to choose which government-funded projects could bring you the best reward. It's easy to become a busy fool by simply 'chasing free money' but that's a big mistake.

We're always ready at www.the-mia.com to answer any of your questions, so contact us any time. We want all in our industry to succeed and grow their businesses, and we must all work together to get through the next six months and enjoy the good times that are ahead.

We've been energy-efficiency specialists since racing started over 100 years ago

Passion fruit

Reflections on Le Mans 2020

There were no fewer than 121 stewards' decisions at this year's Le Mans 24 Hours and the only blessing was the FIA did not seek financial recompense for every breach of regulations.

Time was added to pit stops or, in the case of the final one for the Inter Europol Competition team, a driver missed his driving time by 33 minutes, which was converted into a nine-lap deletion of their race distance.

Teams that checked brake pad wear and accidentally touched the car during refuelling were investigated although there were no penalties, the stewards perhaps realising their zeal had overcome the spirit of racing at Le Mans, but long gone are the days of the 24 hour race through the trees being the Wild West.

Stories of cars that had been written off on Wednesday or Thursday night qualifying, and arriving all straight and perfect in time for morning warm up were fairly regular. Others where drivers had mysteriously found gallons of fuel in the forest that lines much of the circuit were commonplace. Spanners, whole toolboxes even, could be found in the pitch dark out in the trees, and so it was this year when Gabriel Aubry's battery went flat in his Team Jota LMP2 car.

According to the stewards' report, 'The car stopped on track, the driver exited the car and 'phone called his team. A member of the team met the driver and supplied a component, which the driver fitted to the car. The car was then able to continue.

'During the hearing, the team representative admitted to these facts. He also stated that the car would not have been able to continue without this fix.'

Indeed, the car was out anyway and had been leading the category. As one team member said, 'It had to be done.' It is in the record books as 'disqualified'.

It was refreshing to see the old ways had not gone entirely, and that team managers are still willing to roll the dice. But gone are the sacrificial cars on the original entry list that don't stand a chance of pulling together the money to race. We no longer see Swedish gangsters emerge from the truck with helmets on and a slightly different shape and personality, only to then qualify 30s faster than before (or indeed ever again) with nary an eyebrow raised.

Disappointingly, we also no longer have the wide variety of machines, as business overtakes passion. Just eight car makers were on the grid this year – ORECA, Toyota, ByKolles, Dallara, Ligier, Porsche, Ferrari and Aston Martin. Missing were BMW and Corvette, due to the IMSA schedule brought on by the global pandemic, but GTE is now so expensive that small manufacturers can't even dream of entering cars, and therefore GTE-Am (GTE cars that are one year old) is also closed to them.

It was a shame spectators were unable to witness this Le Mans as it was the end of an era. The LMP1 hybrids are now gone, bringing an end (for now) to 1000bhp Prototypes that can blitz the lap records. Toyota wanted to go for it again, to better the 3m14s record set by Kamui Kobayashi, but he abused track limits at one corner on his fastest run on Friday, and so his 2017 record still stands.

Gone, too, could be the LMP2 competition. The class will remain, but there was uncertainty about the driver grading system. The teams voted against mandating a bronze driver in each car but no confirmation of the result came at Le Mans.

Spanners, whole toolboxes even, could be found in the pitch dark out in the trees

When I started going to Le Mans in the 1990s, it was common practice for rent-a-drivers to turn up with a suitcase full of cash and go from team to team to secure a seat. If this Bronze driver rule was applied, that suitcase would be considerably lighter as each of the teams would need such a driver.

All that aside, it was LMP2 and GTE-Am that dominated the grid figures this year. Nearly 80 per cent of the entries, yet both categories are under threat. The new LMDh regulations, announced at Le Mans and covered in this issue, will give the opportunity for the very best of the LMP2 teams to go for the overall win at Le Mans. Indeed, it could be that they *all* buy the cars and have a go.

On one hand that would be fantastic. In the 1990s, those that bought the Courages, the Deboras and the Riley and Scotts knew they would need a minor miracle to win, but they still wanted to be there, racing in the top class, hoping for some of that good old Le Mans magic. On the other, all of the current LMP2 chassis manufacturers are on board for LMDh, and if Porsche and Ferrari step up to provide engines and aero kits, that threatens both GTE and LMP2 in one fell swoop. But if they all stay in the field and go to the top class, while bringing on other GT cars to maintain the balance, that's progress, I suppose.

The world moves forwards and we should enjoy this time as at this race, with these teams and cars, and in this hybrid decade, despite the zealous stewards, we really never had it so good.

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Printed by William Gibbons
Printed in England
ISSN No 0961-1096
USPS No 007-969

THE CHELSEA MAGAZINE COMPANY LTD

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