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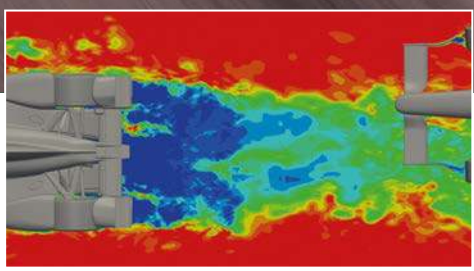

Will F1's 2019 regs improve the racing?

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Macau is an awesome challenge in an F3 car but sadly there's a real chance that November's race might have been the last ever visit for the category

An open and shut case

Should Formula 1 do the sensible thing and enclose the racecar's wheels?

For a moment I would like you to think of tutus. That's right, those frilly, abbreviated ballet skirts. They are more about image than necessity but are integral to the public's perception of the art form. In fact, a collector of such things once paid a whopping $94,800 for the one Margot Fonteyn wore in Swan Lake.

Why would tutus be of interest to *Racecar* readers? Well, think of how Formula racing cars have exposed wheels and an open cockpits, obeying Keke Rosberg's definition: 'Toilets have doors, a racing car you get in from the top'. There are reasons for an open cockpit, but why the exposed wheels? It is certainly not for aiding performance – those four cylinders sticking out produce massive amounts of drag – rather they are a sort of carry over from the early days of racing.

As we know, early cars were a crude extrapolation of a wagon, but with an internal combustion engine rather than horses giving the motive power. Of course, sharing the road with the then dominant form of transport and haulage had its hazards and passengers were often splattered with mud, and worse, so mudguards appeared to make car travel a less soiling experience.

Naturally, of course, the new-fangled contraptions ended up being raced. At first this took the form of great town-to-town contests. However, concerns for public safety led to the races being staged at closed circuits. Competitors would drive their car to the track and take off anything that had weight or could fall off, which also improved the vehicle's aerodynamics.

Open all hours

But when it comes to single seater racing in the here and now, open wheels actually have a number of drawbacks. The main one is that when two cars run close together their wheels may touch. Today's tyres obey a simple law – that the back of a rotating wheel moves up from the ground and the front moves down. So, the connection of high-grip surfaces moving in opposite directions can catapult cars into the air. It was the possibility of high-velocity vehicles being thrown into crowds of spectators that led to protective fencing. Furthermore, while L/D values end up being high, drag figures are risible.

Common sense, then, would see wheels being faired-in in F1, with streamlining and efficiency the main goal. It's not that we haven't seen it before, Mercedes debuted the iconic W196 in 1954 at the French Grand Prix at Reims. The car sported the aerodynamic closed-wheel aluminium 'Type Monza' streamlined body for the high-speed track. Juan Fangio and Karl Kling claimed a one–two finish, and Hans Herrmann posted the fastest lap. However, the same body was to be used only three more times: at Silverstone, Monza, and Monza again in 1955. One problem with the design was the difficulty of judging the overhangs and the cars could be seen considerably 'modified' after bashing cones, bales and other trackside impediments, not forgetting other cars, too.

Solution enclosed

So here is my solution: let's have Formula 1 with closed cockpits (thus eliminating the Halo) and faired-in wheels in the interest of aerodynamics, safety and also to act as drops for my eyeballs, which are almost bleeding from looking at the garishly decorated machines running around grand prix tracks nowadays. Whatever happened to racing's aesthetic sensibilities?

Faired-in wheels are par for the course in LMP1. Could the safety and aesthetics of F1 cars be improved if they had closed bodywork too?

Now, before you lot take umbrage and shoot a plethora of missives, tweets or good old letters to the reader columns of *The Daily Telegraph* or *Racecar*, signed 'Outraged of Milton Keynes', or 'Disgusted of Tunbridge Wells', please note that my modest proposal is reasonable and logical. Anyway, just think of all that added surface area for advertising. Ugh! On second thoughts …

Admittedly, regulating the downforce obtainable by a bigger plan area could be tricky, bringing back the problem of increased cornering speeds and all that comes with it. A bigger plan area could also bring on what has often been an issue with prototype racecars over the years – the cars flipping when the air gets under them.

Paradigm shift

Bearing all the above in mind, why do we still race open wheel cars? Is it for the sake of tradition? Or branding? The absolute minimum, with no required ancillaries such as doors or windshield wipers, consists of wheels, brakes, engine, gearbox in a minimal body that also ticks the box of 'ultra-specialised, no ancillaries, the ultimate speed tool.' However, the less-than-optimal aero drives designers to go to smaller and smaller details to ratchet up the CL values.

When it gets as elaborate as that, the question about simply fairing-in wheels seems apt again. However, it would require a massive paradigm change and could be countered with the argument that we already have something close to that anyway, with the Le Mans prototypes.

Enclosed wheels would also enable closer racing as in touring car championships, where getting up close and personal is part of the game. The shape would have the possibility to be nearer to the styling cues of the manufacturers' road products giving them the incentive to flock to the formula. Oh, wait. Similar to hypercars for LMPs; how did that work out?

Perhaps we should abandon this little foray into 'what could have been' then and simply accept things for the way they are. After all, poet, playwright and famous wit Oscar Wilde once said that fashion was 'a form of ugliness so intolerable that we have to alter it every six months.'

So it may be a sense of romanticism, but some things are just so iconic to a sport or an art form that no one would want to change them, regardless of how anachronistic, unnecessary, or even plain silly they may appear.

The tutu will probably always be associated with ballet and the same seems to go for open wheels on single seater racing cars.

Why exposed wheels? It is certainly not for aiding performance, those four cylinders sticking out produce massive amounts of drag

Change for the better

How Formula 1 can ensure the 2021 regulations will actually make a difference

While we march (uncertainly) towards what was supposed to be radical new F1 technical regulations for 2021, the process increasingly reminds me of the similarly-convoluted negotiations – which will inevitably end in a fudge – concerning Brexit.

The old adage that trying to please everybody ends up pleasing nobody has seldom been more pertinent than in these two examples. However, as motor racing is the subject of this column, there will, I promise, be no further mention of the B word. But talk of fudges there will be, for I suspect, sadly, that where will be a dumbing-down of the massive revamp that was promised for 2021.

Along with power unit revisions, the most concerning fudge is likely to be with the aerodynamics. In order to facilitate overtaking, we have been up and down and sideways over time: less downforce, more downforce; reduction of aero clutter ahead of the sidepods, followed by almost unrestricted bargeboard development. Then the overall wing dimensions (bigger, smaller, bigger again) and a fixed centre span, then do as you like regarding front wings; taller rear wings, lower rear wings, then taller again; narrower and then wider … One can go on.

We *know* that all of this has made only limited degrees of difference to the long-standing problem. The dirty air wake from the car in front radically affects the upper surface-dominated grip and balance of the one behind. Therefore, only a radical solution will work. Nothing so far leaked about the 2021 aero configurations indicates that this is going to happen.

Go to ground

I have gone on about this before, but I cannot understand why the proven solution of doing away with flat bottoms in favour of *controlled* ground-effect underbodies does not seem to be firmly at the very top of the agenda.

The lessons learned in IndyCar and now successfully implemented, especially on road circuits, should be analysed and adopted for the not so dissimilar requirements of Formula 1. Is it that F1 is too proud to copy from IndyCar – perhaps a manifestation of the NIH (Not Invented Here) syndrome? That such an arbitrary panic measure which completely defies good engineering practice, and was first inflicted some 35 years ago, still exists is really quite an insult to Formula 1's much-touted high-technology image.

Floor plan

Starting with a 'spec' underbody, designed by capable engineers who were directly experienced in this field and employed by the FIA, would ease the transition in design time for teams and thus the cost. If deemed desirable to do so (and F1 shouldn't be remotely one-make), restriction on the profile could be relaxed after two or three years as long as the critical dimensions, aimed at restricting the amount of overall downforce that can be generated, remain in force.

Could the problem of F1 cars losing downforce while following closely through corners be solved by a return to ground effect aerodynamics?

I so hope my concerns are unfounded and that we will see the positive change in aerodynamic direction that ground-effect will bring. It is indicative of why changes are needed in grand prix racing that, for all his brilliance, Lewis Hamilton was way off the podium in the recent Mexican GP. This emphasised the fact that if the car isn't absolutely competitive on the day it's not possible to win in a straight fight. Ditto Alonso's McLaren struggles.

Ross Brawn's comment following the disrupted US GP practice, advocating reducing data acquisition throughout an F1 event to introduce more randomness in the results is, however, encouraging. With a similar objective, the first free practice at every event for the previous season's top three or four constructors' championship-winning teams could be mandated as being for their nominated reserve drivers only. This would provide more badly-needed opportunities for young drivers to gain experience and showcase their abilities. Again, the playing field would be more levelled regarding less well-resourced outfits, whose P1 laps with their race drivers installed would be more productive in achieving their final race set-up.

For qualifying and the race, I would go further and restrict the number of power unit software modes to, say, just four – race, fuel save, wet running and damage limitation 'get-home'. Despite, no doubt, protestations otherwise, the engine guys would soon adapt to this. This would help in evening-out performance between teams/engine suppliers, especially during qualifying, and extend the life of PUs.

It seems almost too simple, but tactical no-shows in Q2 for those who have got that far should result in relevant sets of race tyres being forfeited, as this constitutes not keeping faith with the spectators and viewers and should not result in gaining a race advantage.

Penalty appeal

I also hope that the ridiculous grid penalties imposed for replacement of transmissions outside of the mandated number allowed will be dropped. If they are not, then might we possibly see items such as suspension parts and driveshafts being designed to fail sacrificially in an impact without damaging the transmission, thus avoiding replacement? This is surely not beyond the wit of clever engineers.

Even under the revised 2019 technical regulations (see page 30) we should see more of the closer competition that livened-up grands prix this year, especially with Red Bull anticipating much more grunt from new partner Honda's contribution. But a word of caution. More power/torque doesn't always automatically translate into the full gain of overall performance expected. Increased tyre degradation, possibly more cooling and greater fuel consumption, allowance for added braking capacity and greater transmission loads which might add weight, these are all factors that can chip away at the computed advantage. Nonetheless, it's reasonable to assume that the Red Bull cars will soon be able to challenge consistently for wins on all circuits, which can only be good.

That such an arbitrary panic measure, inflicted some 35 years ago, still exists is really an insult to Formula 1's much-touted high-technology image

The new generation

As Formula E enters its fifth season with a brand new chassis and a vastly uprated battery, *Racecar* analyses the unique set of technical challenges both teams and manufacturers will face

By GEMMA HATTON

Compare and contrast: exploded views of the new Gen2 racecar (above) and the original Formula E car (left)

The circle of life of a championship usually starts with restrictive rules, minimal development and a few privateer teams. The chassis and major components are therefore common between them and this equalising of performance generates competitive racing, which is designed to attract new fans. More eyes on the racing gets the sponsors interested as their investments suddenly become a lot more profitable. The consequent more money in the pot then catches the eyes of other race teams, who bring their drivers, engineers and mechanics along with them.

If all goes to plan, the championship will snowball to success and only at this point will the big manufacturers want to take their slice of the pie. We are then treated to some sweet years of thrilling racing where privateers and manufacturers compete against each other and no one knows who will be on the podium. Sadly, this doesn't last for long as the voices supported by the big bucks are usually those that are listened to. No longer do manufacturers want to race to simply promote their brand, they want to race to develop new technologies. This forces the hand of the governing bodies, who will open up the rules to satisfy the demands of the manufacturers, while trying to avoid turning the series into a race of investment.

In order to compete the privateers have to dig deeper and deeper into their pockets, but as the manufacturers continue to collect more

Formula E is one of the few categories that is currently on an upward spiral of success

trophies, the privateers gradually fade into the background. The survival of the series now relies on a few large manufacturers and if any pull out, the others have fewer competitors and therefore less of a point to prove. The once-successful series can quickly become a one-horse race, which is of no interest to anyone. Often, the only way to save the championship is to go back to basics by restricting the rules and reducing the costs, in the hope of encouraging more race teams to take part.

LMP1 is currently entering this phase, with only one manufacturer; Toyota. Therefore, the ACO is formulating new rules, negotiating cost cuts, common parts and standard tech to entice new competitors for 2020. F1 is heading towards a similar fate as Mercedes' dominance is leading to predictable podiums which the FIA is hoping to address with budget caps, simplified aero and fewer energy recovery systems.

Sparklife

Formula E, however, is one of the few categories that is currently on the upward spiral of success; the racing is competitive and manufacturers, drivers and engineers are all battling for a spot on the start line. Season 5, kicks off in Saudi Arabia in mid-December, and the all-electric formula has attracted an impressive 11 teams, seven of which are manufacturers. These include the likes of BMW, Audi, DS, Jaguar, NIO, Nissan and Venturi. The impressive driver line up is also impressive as Formula E regulars Sebastien Buemi, Lucas Di Grassi and Jean-Eric Vergne race alongside Le Mans winner Andre Lotterer and Formula 1 drivers such as Pascal Wehrlein, Felipe Massa and Stoffel Vandoorne. So why does everyone want to race in Formula E in Season 5?

For a start, there are the new cars. After four years of the SRT01, or Gen1, racer, Spark Racing Technologies has developed a brand new Gen2 car; the SRT05e. The futuristic front fenders, giant diffuser and rear wing concept are as radical as the new technologies hidden within the chassis. The most impressive of these is the all-new battery from McLaren Applied Technologies, which now has 52kWh of energy capacity (compared to 28kWh last season), equating to 85 per cent more usable energy compared to the Gen1 batteries supplied by Williams Advanced Engineering. The FIA has also opened up the rules, allowing teams to

TECH SPEC: HEAD TO HEAD *

	Gen1 (season 4)	Gen2 (season 5)
Battery capacity	28kWh	52kWh
Battery weight	310kg	385kg
Battery cells weight	186kg	272kg
Number of cells	165	5,852
Battery density	103.23Wh/kg	165.33Wh/kg
Cell power density	1.4kW/kg	2.2kW/kg
Cell energy density	174Wh/kg	232Wh/kg
Volume	~310L	~321L
Max Power – qualifying	220kW (295bhp)	250kW (335bhp)
Max Power – race	180kW (240bhp)	200kW (270bhp)
Max Power – Fanboost	220kW	250kW
Max Power – regen	150kW	250kW
Charging time	n/a	~45mins
Braking system	Hydraulic	BBW
Transmission	RWD	RWD
Tyres	Michelin	18" Michelin Pilot Sport
Minimum weight (incl. driver)	880kg	900kg
Length	5000mm	5160mm
Width	1780mm	1770mm
Height	1050mm	1050mm
Front track	1528mm	1553mm
Rear track	1492mm	1505mm
Maximum ride height	75mm	75mm
Wheelbase	3100mm	3100mm
Max speed	225km/h (140mph)	280km/h (174mph)
Acceleration 0-100km/h	3.0s	2.8s

*Based on figures supplied by Formula E and the FIA

The Formula E car consumes so little energy driving around at 50km/h behind the safety car that the subsequent laps of the new time-based races can be completed at a faster pace

Formula E

The futuristic design of the Gen2 has revolutionised the aerodynamics of a formula car, with no rear wing and covered wheels. There is, though, an enormous diffuser

fully utilise this extra available power. The qualifying modes have now increased from 200kW to 250kW, while the race modes have also gone up, from 180kW to 200kW.

Going solo

This astounding technical achievement means that one battery can now last the entire race – so no more mid-race car swaps. 'These were often crazy car changes that were becoming risky in Season 4 after the minimum pit stop time was abolished,' says Chris Gorner, technical director at Envision Virgin Racing. 'Running two cars was always more time-consuming and required significant organisation and planning from an operational point of view. However, at least with two cars, if there was any damage, which is likely on the types of tracks that Formula E uses, the two cars enabled some crossover. But in Season 5, if the driver crashes it will be game over until the car is repaired.'

From a technical standpoint this is excellent news, as swapping cars because the batteries don't last was not exactly the best demonstration of electric vehicle technology. However, we all appreciate the entertainment value of pit stops, and so a full race without them might not fill you – or a team's strategist – with too much enthusiasm. To address this Formula E has completely revamped its race format by introducing time-based races as opposed to lap-based races.

'There is no longer a set number of laps for each race, instead the race will last 45 minutes plus one lap,' explains Phil Charles, technical manager at Jaguar Racing. 'This means that there is a moving target on the lap number, which is based on the lead car or expected lead car's pace. It also means that the engineers will need to constantly recalculate energy targets based on the expected number of laps remaining. Therefore, there will still be a significant strategic aspect for the fans to follow as the drivers will still need to manage their energy and power levels to succeed.'

Yellow fever

This management is relatively simple for a conventional race from start to finish. However, add in the complication of full course yellows and safety cars and suddenly the strategy will have to completely change. 'Let's take the example of the Paris ePrix where the lap time is around one minute,' says Thomas Chevaucher, technical director at DS Techeetah. 'During the 45-minute race, you will complete roughly 45 laps. If there is a safety car the lap time will increase to something like three minutes, so a safety car for three laps will take around nine minutes. The Formula E car is so efficient that driving around at a constant 40 or 50km/h behind the safety car actually consumes very little energy. The drivers are not braking so there is little recuperation, but they are not accelerating either, so the energy consumption is more or less nothing. Based on this, three laps behind the safety car will take the same amount of time as completing nine laps at race pace, so the race is effectively six laps shorter. Therefore, the energy available for the rest of the race will be normal plus the six laps, so the pace will be much quicker for the rest of the race, which will create a good show.'

Game theory

Other strategic complications lie in the gaming gizmos, such as Fanboost, where drivers receive an extra 100kJ of energy, via a fan vote, which can deliver between 240 and 250kW power (in a time time period decided by the team) and, new for Season 5, Attack mode. 'This system allows drivers to engage 225kW for a period of time determined by the FIA ahead of the race,' says Charles. 'This higher power setting can be activated multiple times up to a total of eight minutes during the race. There will be an attack zone marked on the track with three timing transponder loops inside it. To activate, the driver must push an arming button and drive through the attack zone with the transponder registering all three loops along its length. There will be a five-second time window to arm the system before the driver can activate it.'

This astounding technical achievement means that one battery can now last the entire race

If drivers use an attack mode in addition to Fanboost then that is up to an extra 50kW of power; it's actually quite a technical challenge for the transmission, motors and inverters, to be able to deliver that amount of power.

Of course, racing with only one car now increases the need for reliability as well as bringing an emphasis on the driver's skill in managing the performance of the brakes and

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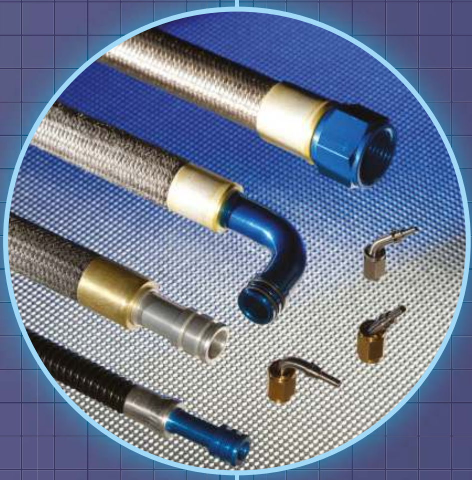

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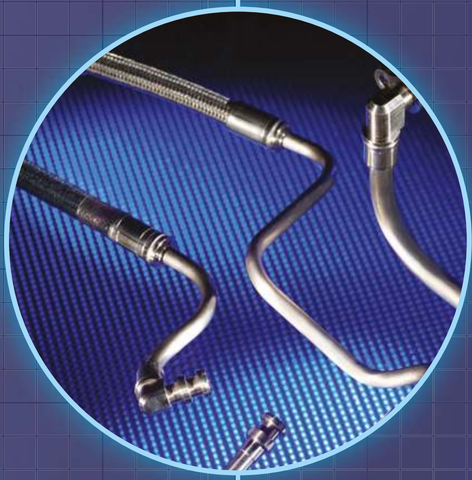

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tyres. Previously, this was less critical as the driver knew that at the pit stops they would be jumping into what was effectively a new car. Now, tyre lock-ups, damage, and running issues will have to be managed until the end of the race, otherwise it will be game over.

'Having one Jaguar I-TYPE 3 per driver places a large amount of significance on any damage or issues incurred during practice and qualifying,' says Charles. 'Formula E is extremely busy with Practice 1, Practice 2, qualifying and race sessions all packed into one day. In Season 3 or 4 if the driver crashed or if there was a mechanical issue you could jump into the other car and carry on your programme. But in Season 5, any significant damage or issue will limit running until car repairs are complete. The most dangerous time will now be in qualifying as any significant damage caused could risk missing the race altogether.'

'It's going to be another interesting aspect to the race strategy because if a driver overheats their tyres, they are no longer able to restart the race with fresh tyres on the second car,' says Chevaucher. 'Therefore, the drivers will have to manage their tyres until the end of the race, which will be a big challenge to try and keep them within the optimum window.'

Compound interest

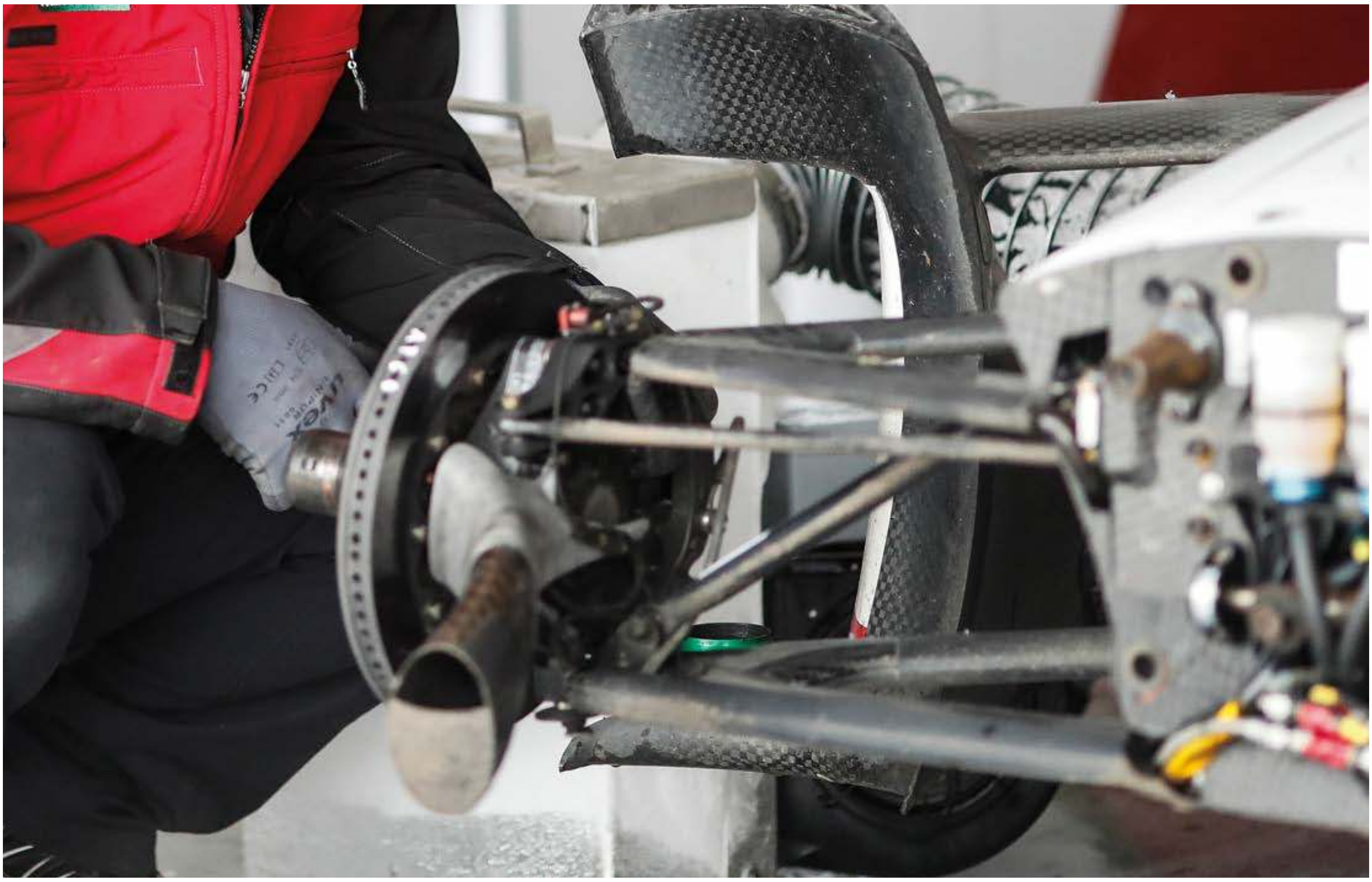
Michelin has been the sole tyre supplier since Formula E began in 2013. In previous seasons, the Michelin design was robust, with minimal degradation, quick warm up, and it was capable of performing in both wet and dry conditions. However, for Season 5 the tyres have to last the entire race and to add to Michelin's headache the FIA demanded a softer compound with weight taken out of the construction. Although this is not quite as big a challenge as you may initially think. The layout of a Formula E circuit is usually made up of short, sharp corners; rarely subjecting the tyres to long lateral loads, where graining and consequently degradation mostly occurs. Furthermore, the Gen2 only has approximately one third of the downforce of an F1 car, so overall speeds are much lower. Add to this the fact that Formula E street circuits often have less grip and the resistance from the energy recuperation means the drivers are not braking as hard. Therefore, it's clear why a softer compound is more feasible in FE than F1.

Despite this, the increased degradation compared to previous seasons will become more of a strategic factor, as was discovered in testing – although the Valencia circuit has higher cornering speeds than the usual Formula E tracks. But could car performance be tyre limited rather than energy limited towards the end of the race for the first time?

Could the performance of these new electric racecars now be tyre limited rather than energy limited towards the end of the race?

Season 5 also presents another challenge for the Formula E teams and the drivers; the introduction of brake by wire on the rear axle. 'This is significant for energy recovery as it directly impacts the amount of energy that can be recovered when braking,' says Charles. 'In Season 4, all teams had to use the same brake bias adjuster and so were limited to the same brake bias range. That brake bias range had an upper limit that meant when you pushed the brake pedal you would still have some hydraulic braking occurring in the rear circuit. If the driver pulled the regen paddle on the steering wheel they would be braking the rear axle with the MGU through the gearbox and driveshafts and if they pushed the brake pedal as well, they would then be braking through the discs and the pads too. All of that rear retardation was not balanced by the front hydraulic brakes.

'This meant that the drivers tended to brake first with just the rear axle using the regen paddle,' Charles adds. 'In Season 5 the addition of the brake-by-wire system means that the



Formula E

With Gen2 cars featuring brake by wire on the rear axle, balancing the amount of braking from the regen with the battery state of charge while adjusting brake bias poses a challenge

The new batteries from McLaren Applied Technologies now last an entire ePrix, with no mid-race car swaps. Drivers must manage the tyres and brakes for the whole race

racecar can effectively "disconnect" the rear hydraulic brakes. So now a control system can be used to blend in the correct amount of regenerative braking on its own at the rear axle – along with hydraulic braking if it is needed – in order to balance the front hydraulic braking. This means that more energy can be recovered when simply pushing the brake pedal.'

Charged up

The shape of the front to rear braking torque bias throughout the braking phase along with the blending strategy will be one of the tools that engineers can use to not only optimise braking performance but also extract the most from the tyres in Season 5.

'There is one more complication,' says Charles. 'At the start of the race the battery is fully charged – at around 97 per cent state of charge – and will not allow any recharging. In fact, the driver cannot fully regen until somewhere between a quarter or third of the race is completed. This means that the blending in the early laps is more dependant on hydraulic and so the amount of energy recovered under the brake pedal is significantly reduced.'

This behaviour requires the brake bias to be adjusted throughout the race. During the first laps, where the state of charge of the battery is high and so there is minimal regen through the rear axle, the brake bias is rearwards. However, as the state of charge of the battery decreases, and therefore the amount of regeneration increases, the increased torque provided by the regen contributes to the rear braking and so the brake bias has to be moved forwards.

'Essentially, the rear brakes will only be used at the beginning of the race because the battery cannot do a lot of regen,' says Theophile Gouzin, technical director of Spark Racing Technologies. 'After three or four laps, the regeneration of the battery is so large that the drivers won't need the rear brakes at all. It would have been good to design the new car without rear brakes, but instead we reduced the disc size, the ventilation and the caliper size to try and save weight.'

To simplify this process, Formula E switched to Brembo as the single supplier of the mechanical brake unit, rather than Alcon which previously supplied the calipers and master cylinders – Carbon Industries had supplied the carbon materials. Despite reducing the weight of the rear brakes, the addition of the electric motor and hydraulic pump required for brake by wire has increased the overall weight of the system by a few kilos. To help mitigate this effect Spark has worked with the FE teams to integrate fixture points within the cockpit of the chassis so that they could integrate the system to achieve their desired weight distribution.

'After three or four laps the regeneration of the battery is so large that the drivers won't need the rear brakes at all'

Increased pace

Another factor that Spark had to consider when developing the STR05e chassis was the effect of the increased pace the drivers may run at during the final stages of the race as a result of any safety car periods. This will result in larger amounts of energy being dissipated through the brakes. This, in addition to the new fenders covering the front wheels, could lead to the brakes overheating, particularly when steered, as the cooling airflow to the calipers and discs is now blocked by the fenders. This is why Spark has allowed the teams to choose from several options of brake ducts. This had previously been forbidden in order to control costs.

With Formula E revolutionising racing, the continual and tricky balancing act of achieving futuristic designs while maintaining functionality and performance has been the biggest challenge throughout the chassis design. 'When you work with designers, they will always come up with shapes that look great, but often don't work with the airflow, so it has been our job to transform their designs into something that is slightly less good-looking but that works,' says Gouzin. 'The average speed of the racecars in a city centre is around 140km/h and to generate a lot of downforce at those speeds you would have to develop crazy wings. So aerodynamics is less important in Formula E and the regulations have been written like that, which is good because it allows closer racing and [helps to] controls costs.'

'Despite the radical new look of the Gen2 car, surprisingly the peak lift and drag numbers are actually quite close, although the way the lift is now generated is quite different,' says Charles.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‘From our point of view the weight is not an issue because it is the same for all’

'The rear wing is fundamentally gone, and the floor is much bigger. The aero map shape is also quite different with peak lift coming at quite different ride height combinations compared to the Gen1 car. Another significance is that the adjustable front and rear wing flaps are now gone. In fact, there is no adjustment on parts of the rear wing on each side of the car and on the front there are only two interchangeable front flap options – 15- and 20-degree flaps. This means that ride height change, and therefore rake angle, become an even more important method to adjust the aero balance.'

Weight and see

From a chassis perspective, accommodating a battery that lasts twice the distance can cause serious weight and packaging dramas. 'Initially there was some doubt over whether the Gen2 car would be light enough to maintain the level of performance of the Gen1 car because at that time of the project we didn't know whether the battery would meet the minimum weight,' says Gouzin. 'So each time McLaren made progress with the battery technology, we had to save weight elsewhere in the racecar. Also, if the structure and shape of the battery was too complex, then this can compromise stiffness, so you have to add weight to recover that stiffness. We worked closely with McLaren Applied Technologies to develop a battery system that was much easier to integrate, despite the larger capacity, and that retained its stiffness.'

This process was also made easier by the fact that the Season 5 battery tender was for three years, whereas the duration of the previous supplier was unknown and so Spark had to design the battery to be completely detachable from the driver's cell in case the supplier changed. However, the Gen2 car has incorporated the battery safety cell together with the driver safety cell, saving weight.

Another addition to the Gen2 car which has increased the weight is the Halo. The Halo design used in Formula E is exactly the same as the one used in Formua 1 and weighs in at approximately 7Kg. 'The most important aspect about the Halo is that it can save lives. Unfortunately the purists have taken a long time to accept it,' says Gorner. 'With regard to performance it is all relative, perhaps more so in Formula E, as there is no alternative aero interaction. From our point of view, the weight is not an issue because it is the same for all. Formula E is not about developing amazing aero solutions, but assisting manufacturers to accelerate their growth in e-mobility and produce efficient road relevant vehicles to win the race against climate change.'

Another addition to the Gen2 car is the Halo, which is the exact same specification as that used in Formula 1

'Originally we did all the project work without the Halo and once we had made the very first monocoque and had passed the FIA tests, the FIA then told us that the Halo was 100 per cent confirmed,' says Gouzin. 'It was not a surprise, but a big rush to re-engineer the integration of the Halo into the racecar. We had no choice but to pass the homologation tests first time with the second monocoque with the Halo because otherwise the entire programme would have been delayed. So there has probably been some additional trade-off, such as a few extra plies of carbon to ensure that the chassis did pass first time.'

‘Despite the radical new look of the Gen2, surprisingly the peak lift and drag numbers are actually quite close to the older car’

Tech freedom

The Gen1 car took 10 days to manufacture the chassis from the first ply in the mould to the last machining process. The Season 5 Gen2 car took 30 days, which highlights the complexity and detail now required from the chassis design.

Yet while this chassis is the same for everyone, all the components rearwards of the battery are open for the manufacturers to develop. 'One part of the car which we are mainly working on is the electric motor and inverter,' says Chevaucher. 'From Season 2, all the manufacturers have been developing their electric motors and it is difficult to imagine the kind of steps that we have made in terms of efficiency and weight saving. We are now so close to 100 per cent efficiency that it is difficult to make any more big improvements. However, we are now focusing on the range of efficiency of the motor and inverter so that this maximum efficiency can be used for most of the time.

'In previous years, some manufacturers were using gearboxes with several ratios which was due to the limited range of efficiency of the motors available at that time,' Chevaucher adds. 'Now, I think all the manufacturers are running single speed gearboxes thanks to the huge improvements in this electric technology.'

Overall, the engineering behind the Gen2 car is set to break new boundaries, particularly in battery technology and efficiency. Add to that the clever manipulation of the rules to achieve competitive racing and it's fair to say that the anticipation for the start of this new generation of racing is extremely high. However, with so many big manufacturers now on board, Formula E's next big challenge is to try and retain the interest of these motorsport giants, whilst keeping the series viable for the privateers. 'At the moment it is still possible to be competitive as a privateer with the manufacturers without having a huge budget,' says Chevaucher. This is perhaps the secret behind Formula E's success; and maybe other championships should take note.

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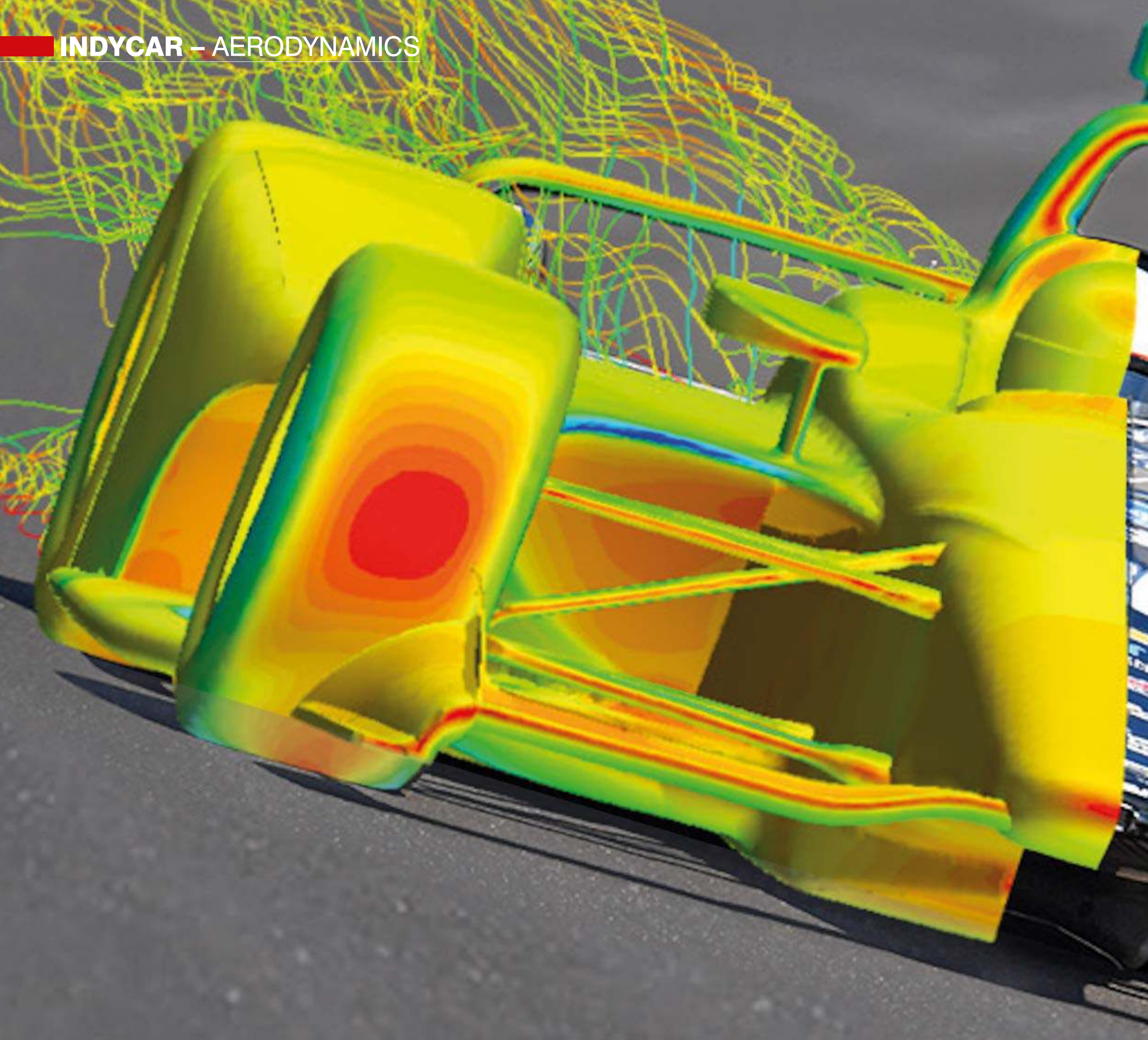


Where science meets art

How IndyCar has worked, and is still working, to find that tricky balance between making on-track passing possible at Indianapolis while retaining the fundamental racer's skill of overtaking

By STAN SANDOVAL

Many of the most iconic moments in the history of the Indianapolis 500 have been overtakes; daring passes completed at the last possible second by the bravest drivers in the world. Other times, the biggest drama comes when the pass isn't quite completed, and instead the race back to the finish line is lost by mere inches, coming up agonizingly short.

There is an art and a science to overtaking at the Indianapolis 500, and mastering this skill is often the difference between glory and heartbreak. But perfecting overtaking has always been a moving target; as technology evolves and the cars change, the type of racing seen during the Indy 500 changes as well.

In May of 2017 slipstreaming reigned supreme as the go-to method for passing. The suck up effect was powerful, which made the leader a sitting duck. Therefore, *when* a driver made a move seemed to be more important than *how* that driver made a move.

Fast forward to May 2018, and the technique to set up a pass was now a lot more nuanced: it was all about setting up your prey and pouncing at the last possible second. Tactics and bravery became the requisite skills to overtaking at Indianapolis for the 2018 race.

The difference in how overtaking at this great race plays out can be largely attributed to two things: tyres and aerodynamics. The 2017 season marked the last year of manufacturer-developed aero kits and 2018 saw the start of the universal aero kit, called the UAK18. This new outfit for the Dallara DW12 chassis brought a huge aesthetic change, but also an interesting opportunity for IndyCar: the chance to dictate the aerodynamic behaviour of the entire field, and therefore, improve the racing. With the

IndyCar's main goal was clear – to make overtaking exciting and skilful

UAK18, IndyCar's main goal was clear: to make overtaking exciting, dramatic, and skilful.

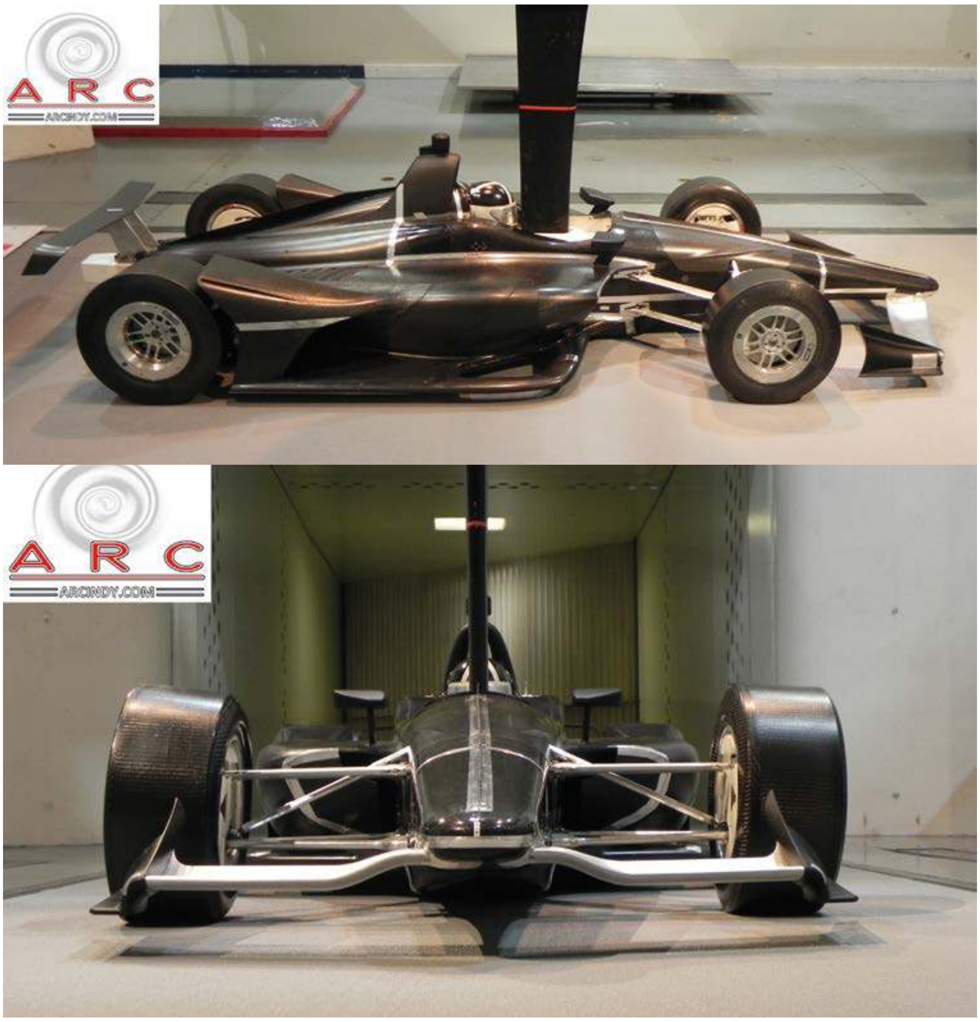
With all this in mind IndyCar has implemented a study to understand how aerodynamics affects overtaking by conducting two-car CFD simulations of both the UAK18 and manufacturer aero kits from 2017. Given the difference in the racing between the 2017 and 2018 Indy 500s, the objective was to understand any aerodynamic characteristics that led to the large slipstream effect in 2017 and the increased difficulty in following closely in 2018.

Using a CFD software suite designed specifically for automotive aerodynamics called Elements, developed by Indianapolis-based Auto Research Center (ARC), various following two-car configurations were simulated for each aero kit. IndyCar and ARC have spared no expense in conducting these simulations. Each was modelled considering turbulent, unsteady, and incompressible flow, making these some of the most advanced automotive computer simulations in the world.

Calculating simulations with this level of complexity required serious computing power. R Systems NA Inc's experience in motorsport, large capacity, and expertise in cluster configuration created an optimal solution. IndyCar ran hundreds of jobs on its Broadwell E5-2697Av4 nodes with 32 cores each, 256GB RAM, and Non-Blocking FDR Infiniband. With the CFD simulations in place and the proper computing power now acquired, hundreds of simulations were carried out. From these, some striking aero differences between the two IndyCar aero kits were revealed.

Initial single-car CFD simulations of both the 2017 and 2018 aero kits were validated against moving ground wind tunnel results conducted by ARC in Indianapolis. Once this baseline check had been completed, two-car simulations began. Multiple two-car simulations were carried out for both aero kits, with the position of the following car varied in order to get a sense of how each aero kit behaves when battling with another car on track.

Bravery and skill is needed when passing at Indianapolis; as Alexander Rossi certainly demonstrated at the 2018 Indy 500



The 50 per cent scale UAK18 model in the ARC Wind Tunnel during aerodynamic testing. *Courtesy of ARC*

Analysing the wake

The wake generated by each aero kit was a hugely influential factor on how each car raced during the Indy 500. Understanding the differences in the wakes generated by the 2017 and 2018 aero kits would be key to understanding why the type of racing and overtaking seen at Indianapolis changed.

To start, the wake created by each aero kit in isolation was visualised and assessed. Using the Honda aero kit from 2017 and this year's UAK18, plots of total pressure coefficient were created to show where energy loss in the flow was most prevalent behind the car. From these visualisations, the size, strength, and shape of the wake created by each aero kit could then be observed and compared (see p24).

When viewed from above, **Figure 1** showed that the UAK18 generally had a much larger wake. The wake of the UAK18 also widened as it travelled further downstream. The wake of the 2017 Honda narrowed as it travelled further downstream, and it also appeared to weaken while the UAK18 wake maintained a relatively consistent strength. In **Figure 2**, the 2017 Honda wake grew taller as it travelled downstream, whereas the UAK18 wake maintained a relatively consistent height.

To give some insight into why each wake takes on the shape that it does, streamlines were plotted and colour-coded by velocity for both aero kits in **Figure 3**. These streamlines show that the rear tyres were influential in

Some striking differences between the two aero kits were revealed

determining the shape of the wake. The wheel guards on the 2017 Honda kit were able to control the flow behind the rear tyres; however, for the UAK18, the rear tyres were left exposed. This was a contributing factor as to why the wake of the UAK18 continued to widen while the 2017 Honda wake narrowed.

Similarly, the streamlines behind the 2017 Honda rose as they travelled downstream, while for the UAK18 they stayed in close proximity to the ground, which was also consistent with the shape of the wake. This was due to the 2017 Honda generating more rear wing downforce and therefore upwash, while the UAK18 created a larger percentage of its downforce using the underwing. Still, while some obvious differences in the wake characteristics were found, how these differences affected a racecar following closely behind another and attempting to overtake remained to be seen.

Performance in traffic

One of the most important factors for overtaking is how a car behaves when following closely behind another car. This is when aerodynamic effects like dirty air and slipstream are greatest, but also when an overtake is most likely to occur. IndyCar, ARC, R-Systems and Parallel Works have worked together to use these CFD simulations to quantify how drastically the performance of each aero kit changes when following in traffic by comparing downforce, drag, and balance when in traffic to when running alone. Using the two-car simulation where the following racecar is directly behind the leading car at a following distance of one car length, the change in performance was calculated; see **Figure 4**.

At a following distance of one car length, the UAK18 showed a six per cent greater downforce loss than the 2017 Honda, but the slipstream effect was seven per cent stronger. However, the centre of pressure of the UAK18 moved rearward

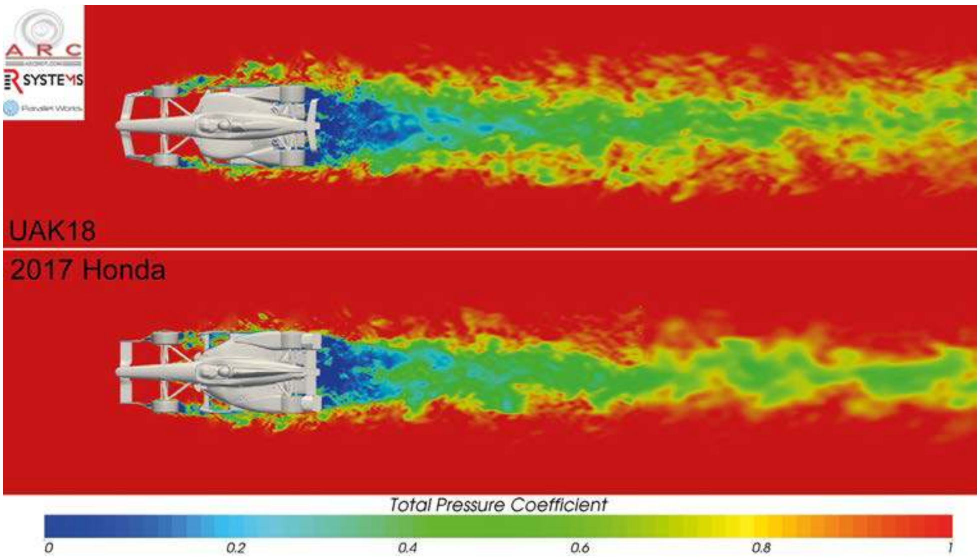


Figure 1: Comparison of total pressure coefficient for the single-car case at the height of the front wing airfoil, as seen from above. The UAK18 bodykit generally had a much larger wake and this also widened as it travelled further downstream

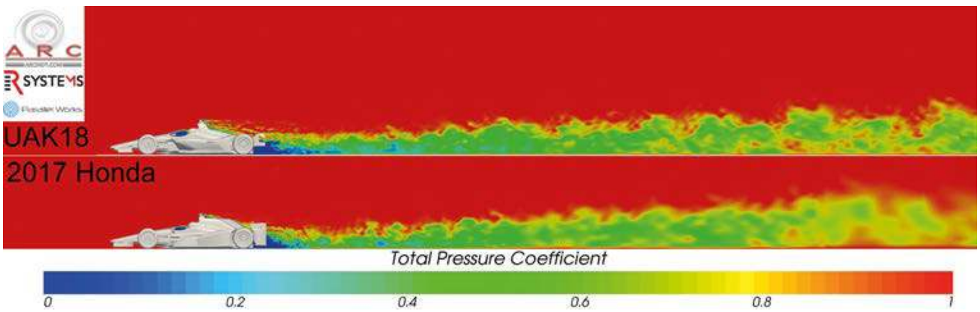


Figure 2: Comparison of total pressure coefficient for the single-car case along the centreline of each car, seen in profile. The Honda wake grew taller as it travelled downstream whereas the UAK18 wake maintained a relatively consistent height

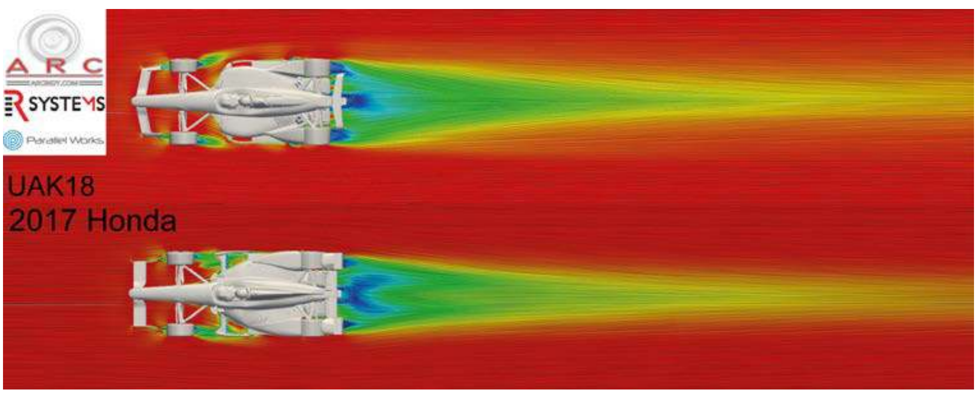


Figure 3: Comparison of streamlines (colour-coded by velocity) for the single-car case at the height of the front wing airfoil, seen from above. These streamlines illustrate that the rear tyres were influential in determining the shape of the car's wake

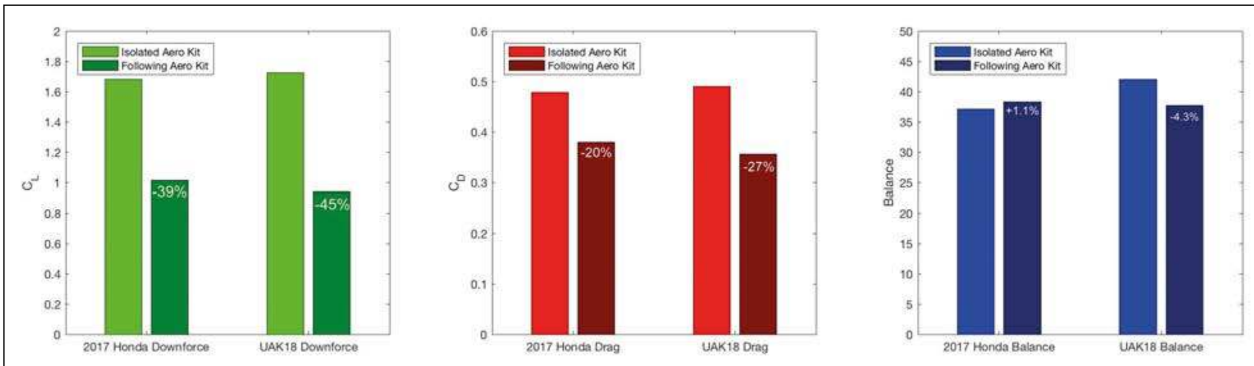


Figure 4: Here's a comparison of downforce, drag, and balance for an isolated 2017 Honda and UAK18, and also a following 2017 Honda and UAK18

'When you get close to other racecars the front goes, and that was the problem'

more than four per cent while the 2017 Honda's aero balance moved forward approximately one per cent. Note how the balance of the following car was set by the drivers to be similar to 2017 in UAK18, but as a consequence the UAK18 has more oversteer when leading. While the loss in downforce and drag were somewhat similar between the two aero kits, the discrepancy in balance shift was large. Drivers and engineers across the paddock agreed, the balance shift in the UAK18 was greater than the 2017, and that this made it difficult to set up an overtake.

'On my own I was loose. But I had to run like that because otherwise I would push in traffic,' says Team Penske driver Simon Pagenaud.

Chip Ganassi Racing engineering manager Julian Robertson echoed this sentiment. 'When you get close to other people, the front goes, that was the problem,' he says. 'It always has done, but you live with it. But this year your tools had to be all one way to even stand a chance in traffic. You had to be loose on your own to be half decent in traffic; it was a big disparity.'

Balancing act

The change in balance was identified as one of the principal causes for overtaking being more difficult at the 2018 Indy 500. Therefore, further investigation was conducted in CFD to understand why there was such a large difference in balance shift between the two aero kits. Surface pressure across the entire car was plotted for both aero kits in order to visually demonstrate where downforce was being lost on the following car. This was then validated numerically by breaking down the per cent downforce loss suffered by the main aerodynamic devices on the racecar between the isolated case and when following behind another racecar at a distance of one car length, as is illustrated below in **Table 1**.

As is evident both visually and numerically, the biggest discrepancy between the two aero kits was the loss of performance experienced by the front wing. The UAK18 front wing appeared to suffer more than the 2017 Honda when operating in the wake. Yet, no evidence of airfoil stall or massive separation was found on either following car's front wing.

So, the effect of the wake of the leading car on the following car's front wing was thought to be the main culprit, given the differences between the two wakes found previously. The effect of the leading car on the following car front wing was investigated to understand just how influential the wake is in determining the front wing performance of the following car.

From **Figure 9** it was evident that the available total pressure in the wake for the front wing to utilise was significantly less for the following UAK18 than the following 2017 Honda, due primarily to the difference in wake characteristics. With this loss of total pressure, the ability of the UAK18 front wing to generate downforce when following closely suffered greatly compared to the 2017 Honda, all due to the wake of the leading car.

Not only did this explain the discrepancy in front wing performance in traffic, but also the disparity in balance shift between the two aero kits. This was seen as the main cause for overtaking being more difficult in 2018

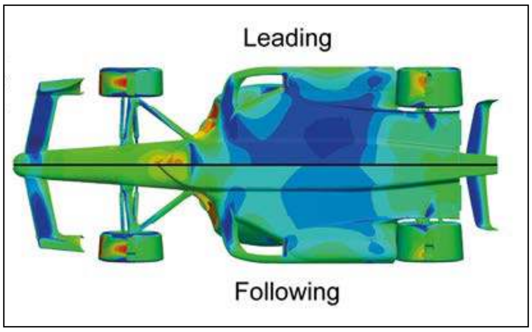


Figure 5: A comparison of the surface pressure distribution for UAK18 when running in front and then behind, viewed from below

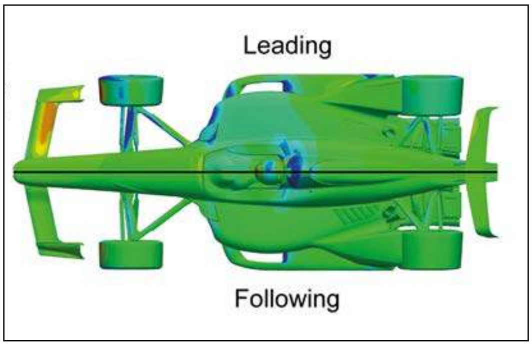


Figure 6: This shows the same comparison of the surface pressures acting on the UAK18, this time viewed from above

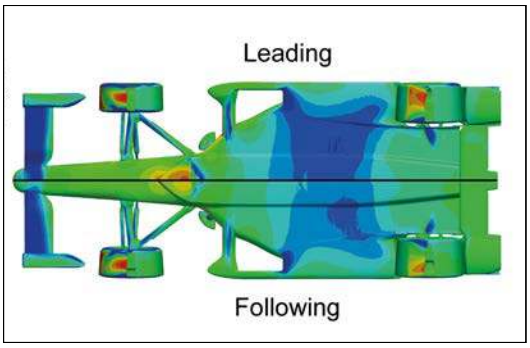


Figure 7: A comparison of the surface pressure distribution for the Honda when running in front and behind, viewed from below

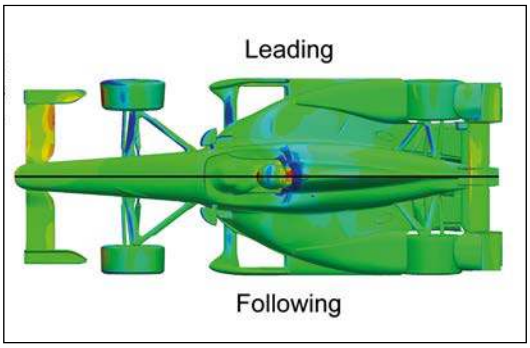


Figure 8: This is the same comparison of the surface pressures acting on the 2017 Honda bodykit, viewed from above the car

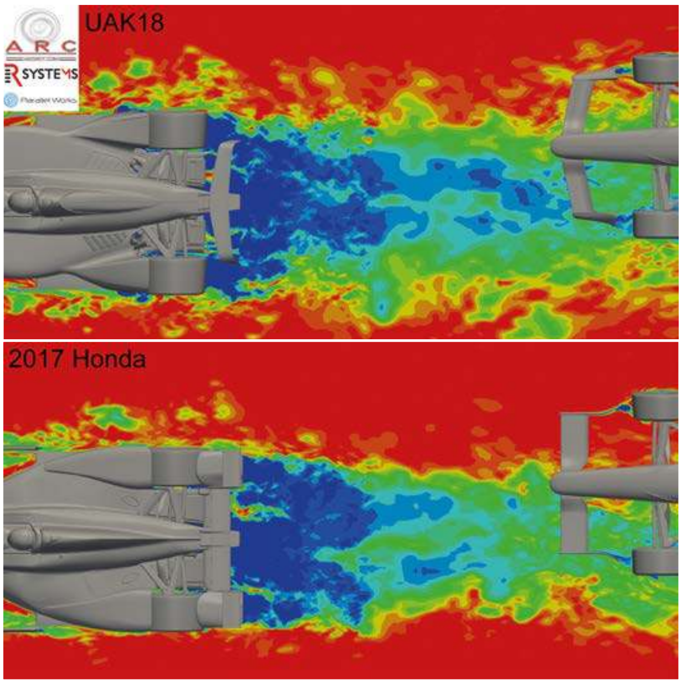


Figure 9: This shows a comparison of total pressure coefficient for the two-car case at the height of the front wing airfoil, viewed from above

Component CL % change	UAK18	2017 Honda
Front wing	-44.684	-16.529
Cockpit and floor	-40.615	-39.571
Rear wing	-4.802	-19.695
Wheel guard	--	-53.794

Table 1: A comparison of per cent change in downforce relative to the single-car case; as experienced by various components on a following UAK18 and also on a following Honda 2017 kit

The UAK18 front wing appeared to suffer more when operating in the wake

The biggest discrepancy between the two aero kits was the loss in performance experienced by the UAK18's front wing

Front wing extensions were made available to the teams at Pocono in 2018 and will now also be used in the 2019 Indy 500

Figure 10: Velocity contours for two UAK18 kits. The predictive map for following-car aero will be used in DIL simulators

compared to the 2017 season, and the solutions to this are already in the works.

These include front wing extensions, which were made available to the teams at Pocono. They will be allowed to use these for the 2019 Indy 500. This allows them to have more front downforce by extending the chord of the airfoil.

Together with Firestone, new tyre compounds and constructions have also been tested on several occasions at Indianapolis in order to give additional mechanical front grip. With the reasons as to why overtaking was more difficult in 2018 identified and remedies already in place for next year, the 2019 Indy 500 is expected to feature more close racing and overtaking, though not without the requisite bravery and skill from the drivers.

Mapping an overtake

Simulations were conducted where the position of the following car relative to the leading car was varied by up to 50 metres in distance and six metres in offset. With these results, a predictive model was developed in order to create a map of aerodynamic performance as a function of following position. With this, the behaviour of both the leading and following cars was calculated at each and every moment during an overtake, as shown in **Figure 10**.

Another vital use of this mapping is its integration with the driver-in-the-loop (DIL) simulator. DIL has become an essential training tool for race drivers, as track time is not always feasible. By simulating two-car situations in CFD and integrating the results in DIL, drivers would be able to experience traffic situations in the simulator, with all the aerodynamic consequences that come with following and overtaking another racecar.

Beyond helping drivers practise following and overtaking, the DIL could also be used to get driver feedback on how an aero kit performs in race traffic. This could be extremely useful for understanding how potential changes to an aero kit will impact the racing on track. Just like CFD, the DIL could be an important tool in developing future aero kits.

Conclusion

Overtaking should always require skill and bravery from the drivers, but it can't be so difficult that it leads to a high-speed parade. However, finding that balance is a very difficult task, as it exists on a knife-edge. With the help of ARC, R-Systems and Parallel Works, a foundation has been laid using CFD to quantify the difficulty of overtaking due to aerodynamics. With this knowledge, future iterations of IndyCar aero kits can be designed with overtaking performance in mind. It can become another design parameter just like a target downforce or spin stability.

In doing this, racing at Indy can be engineered to make it challenging for the drivers and entertaining for fans. Once again, overtaking can become a work of art.

The Honda Performance Development DIL simulator (*Honda*)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With the 2019 Formula 1 technical rules package now set in stone *Racecar* examines the details and asks the most important question of all – will this really improve the show?

By SAM COLLINS

Regulation issues

Formula 1's new owner, Liberty Media, embarked on a project to fundamentally overhaul grand prix motor racing almost before the ink on the acquisition documents had dried. There was talk of making every race a Superbowl, while new types of fan engagement were looked at. The first fruits of this work can already be seen on every broadcast, with revised and more up to date branding alongside a much improved online and social media presence.

But according to Liberty there is still a lot more to come, not least on the technical front. To this end it has quietly been signing up highly experienced technical staff including Ross Brawn and Pat Symonds to create a completely new set of technical regulations for the 2021 season. That work is ongoing, but soon after the 2021 project began another more pressing issue was identified: Formula 1 had, in essence, become a bit boring and predictable. The 2017 technical regulations caused what was already a shortage of on-track overtaking to become even worse, and so the new group of technical experts assembled by Liberty and Brawn set about resolving this problem.

A specific issue relating to airflow around the front wing was identified,

Despite the new restrictions Formula 1 teams still think that there are gains to be had in terms of wheel rim and brake cooling system design

which made it very hard for cars to follow one another closely. Wind tunnel and CFD work was done both by Brawn's group and eight of the F1 teams and from this a draft set of regulations was created. This draft proposed a wider, simplified front wing and a wider rear wing, simplified brake ducts with a number of other detailed changes (as detailed in *Racecar* in August, V28N8). After that draft was circulated to the teams a number of further discussions took place resulting in significant changes to the final published regulations, which then finally appeared at the US Grand Prix.

Detail changes

The core of the new technical rules package remains as defined in the draft regulations, with wider, more simplistic wings and new brake ducts included, but detail changes have been made in all areas.

At the front of the car the overall front wing package from the draft regulations carried through to the final rulebook as expected, with its width increased by 200mm to the full 2m width of the car. In the draft regulations teams were restricted to using just two simple strakes on the underside of the wing but that restriction has been lifted in the final version, giving the designers a touch more freedom – though the shape of the strakes themselves remains far more basic than in 2018.

As the front wings of the cars will be wider they will also be a lot more vulnerable to driver-induced damage. To combat this the rules force teams to use a tougher laminate in the leading 50mm of the wing.

Something which may make the wings even more vulnerable is the extension of the front overhang of the car. From the centreline of the front wheels to the leading edge of the bodywork, the maximum allowed overhang has been extended by 225mm to 1225mm, which should give teams a slightly larger area to work in in terms of aerodynamic development, but it remains to be seen how many will take full advantage of this extra freedom.

Damage to the front wing could result in a slightly harsher penalty in 2019, as the new rules require the nose to be mounted to the front of the monocoque by four equally strong fasteners, and this could increase the amount of time it will take to change the nose in the pits. This is a noteworthy factor because if the new rules work as intended then damaged wings could become more common as one of the main aims of the 2019 regulations is make it easier for cars to follow each other on track, which increases the likelihood of wheel to wheel battles.

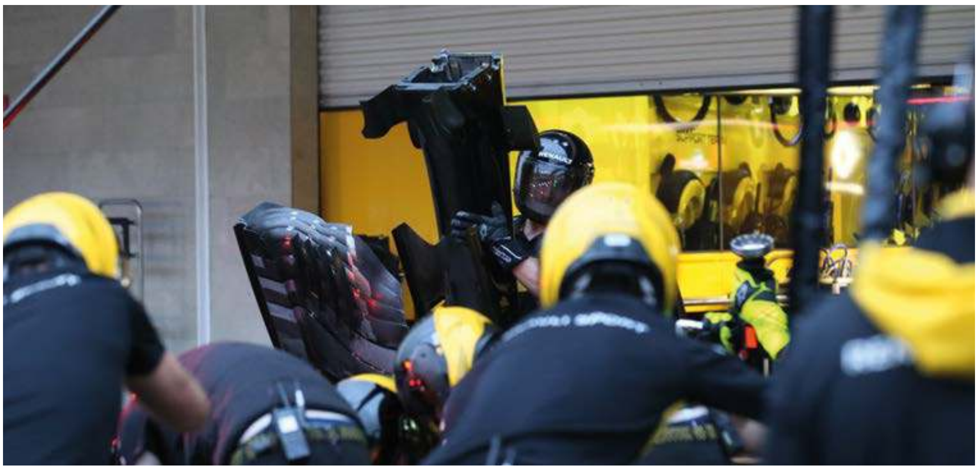
To achieve this the rules aim to make it difficult or impossible for teams to capitalise on the so-called 'outwashing' aerodynamic effect. A key part of this is totally redefining what is permissible in terms of brake duct design. The complex arrays of turning vanes and winglets have all been outlawed in favour of simple units with just a single cooling aperture, with a maximum 50mm circumference (though the aperture does not have to be circular). Currently most teams use multiple apertures and aerodynamic elements so this represents a significant loss in overall car performance.

Additionally, inside the front wheel rims and brake drums no air is permitted to pass through an area of the centre of the wheel, 105mm in diameter from the centre of the wheel nut. This is to end the practice of 'blowing nuts', something which makes a notable contribution to the outwash effect.

Closing loopholes

Further steps have also been taken in order to prevent the teams from coming up with creative ways of getting the very same effect by using various mounting points on the upright to feed air through this area. In 2019 any aperture where suspension legs, elements of the uprights or other brackets meet the ducting, must be sealed so that no air can pass through them. These seals have to be flexible in order to allow the suspension to move, but they also have to be mounted to the upright and not to the suspension members.

The maximum front overhang has been increased by 225mm to 1225mm. Could this be a new area for aero development?



Nose replacements could take longer in 2019 due to a change in the regs; four equal strength fasteners are now required

The rules aim to make it difficult for teams to capitalise on the so-called outwashing aerodynamic effect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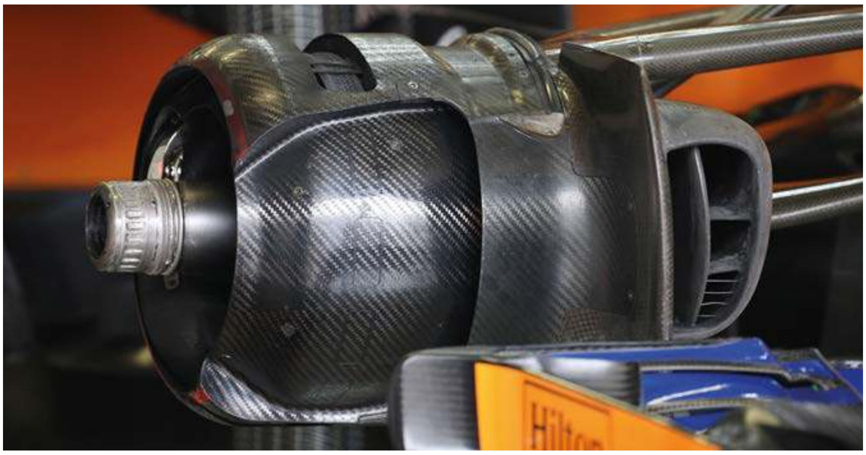


Left: Multiple brake cooling apertures will not feature in 2019

Sidepods have been a major area of development since the start of the 2017 technical regulations

Despite these restrictions teams still think that there are gains to be had in terms of wheel rim and brake cooling system design. 'It is even more important with the 2019 rules because you are struggling to get the front wing to outwash the air as much as you would like,' Renault F1 chief designer Nick Chester says. 'So if you can do more in the wheel it becomes even more important.'

The sidepod area

Sidepods have been a major area of development since the 2017 technical regulations were introduced, with teams pushing to get an aerodynamic gain from relocating the upper side impact structure. Three schools of thought developed in terms of the design of this part of the car, with Ferrari's short sidepod layout using a variety of winglets and turning vanes to ensure legality (a style copied by a number of teams), Mercedes and others sticking with a conventional layout and Sauber using a unique but seemingly effective multi-ducted solution. Much of this diversity of design is about maximising the aerodynamic potential created in the wake of the front wheels, and just ahead of the sidepod there is an area of regulatory freedom.

This bargeboard area is considered to be very powerful in terms of aero performance, but the area of freedom has diminished for 2019 with the maximum height of components in this region reduced from 475mm down to 350mm. In addition to this the regulations relating to the leading edge of the sidepod have also been updated.

'We've got rid of all the furniture on the front wing, it's a wider span, the brake duct winglets have gone, the bargeboard area is very different and what that all does is it gives you much worse wheel wake control,' outgoing head of vehicle performance at Williams, Rob Smedley, says. 'We've found some really clear directions of where we need to work to recover the performance and it will be very, very interesting at the start of the season, to see the different concepts that come out. Then you'll probably find that there'll be a really quick convergence as usual as we take the best concepts from all the cars and blend that into the normal lookalike Formula 1 car.'

The bargeboard height will be reduced in 2019; giving the teams less scope in what is a fruitful area for aero development

Smoke and mirrors

Sitting just above the bargeboard area of the car is a component which has seen both controversy and innovation in 2018; the rear-view mirrors. For 2019 the rules relating to the mirrors are entirely new, and this is a direct result of the developments of one team; Ferrari. When its SF71H was launched at Maranello ahead of winter testing it was immediately apparent that there was something unusual about the mirrors on the car. Ferrari had created a ducted housing

Ferrari's trick wing mirror designs in 2018 prompted the FIA to clamp down on the use of the supports as aerodynamic devices

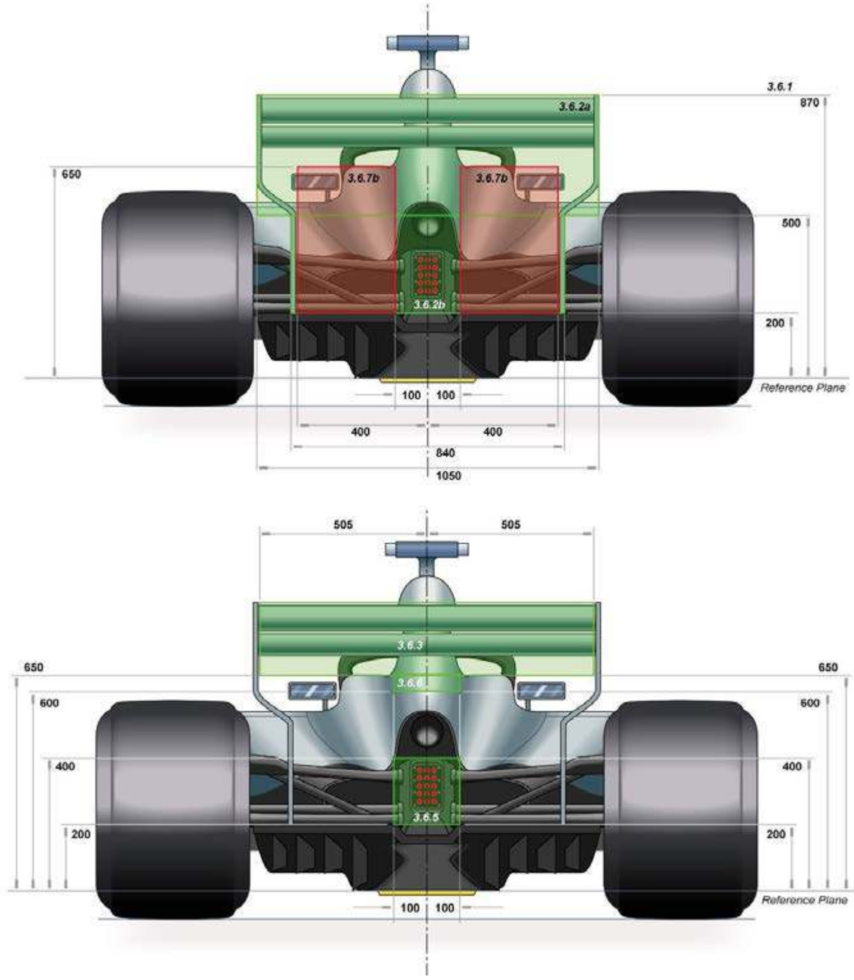
'It will be very, very interesting at the start of the 2019 season to see the different concepts that all the Formula 1 teams come up with'

in order to reduce drag (See May's *Racecar*, V28N5). Later in the season other teams copied this design but Ferrari went a step further, mounting the mirrors directly to the Halo. This was specifically allowed in the 2018 regulations, but the stalks Ferrari used were clearly designed for aerodynamic gain, and caused consternation among the technical departments of other teams.

A technical directive later outlawed Ferrari's initial approach, but now that it is fully aware of what could be done with the mirrors the FIA has really cracked down on mirror design in the new regulations. The position of the mirrors has been very tightly restricted with the centre-point of the reflective surface having to be located between 575mm and 700mm forward of the rear edge of the cockpit, and between 500mm and 550mm from the centreline of the car. They must also be between 640mm and 680mm above the reference plane.

This does not stop them being mounted on the Halo, but means that the design of the mirror stalks will be crucial, and here the new rules are far more restrictive; with only one support allowed to link the mirror housing to the monocoque. However, a second support is also allowed to connect to the surrounding bodywork.

The mirror housings have also been more strictly defined, along with the mirrors themselves. In 2019 the reflective surface must be rectangular – 150mm wide and 50mm high – with a radius of up to 10mm allowed on each corner. The housing around it offers a 15mm area of freedom around the mirror glass, with the housing able to extend 60mm forward of the glass and 15mm rearward, though this still allows for Ferrari's low drag housing.



Rear wing height has been raised to give better rear visibility. It will now be 870mm, up from 800mm in 2018

Formula 1 will now feature LED lights in the trailing edge of the rear wing endplates; as used on LMP cars

Winging it

Rear visibility was actually the main reason behind another major change between the draft and the final regulations, and it has a major impact on the design of the rear wing. In the draft regs this was to not only be wider but also slightly (20mm) taller, while in the final version the height has been elevated even more, up to 870mm compared to the 800mm maximum height of 2018. This means that the wing elements do not impede rear visibility.

New LED light strips will be added to the trailing edge of the endplates, similar to those used currently on Le Mans Prototypes. The purpose of the lights is simply to make the rear of the car more clearly visible in wet conditions, as the 2018 specification single rain light can be hard to see.

The higher rear wing is likely to influence the overall aerodynamic balance of the car, but despite being confirmed relatively late the teams have apparently not found this to be an issue. 'With the rear wing in particular, although it was quite late, there was a fair amount of discussion that preceded it that indeed investigated alternative ways of increasing visibility, like reducing the rear wing box height,' Ben Agathangelou of Haas

The higher rear wing is likely to influence the aero balance of the car

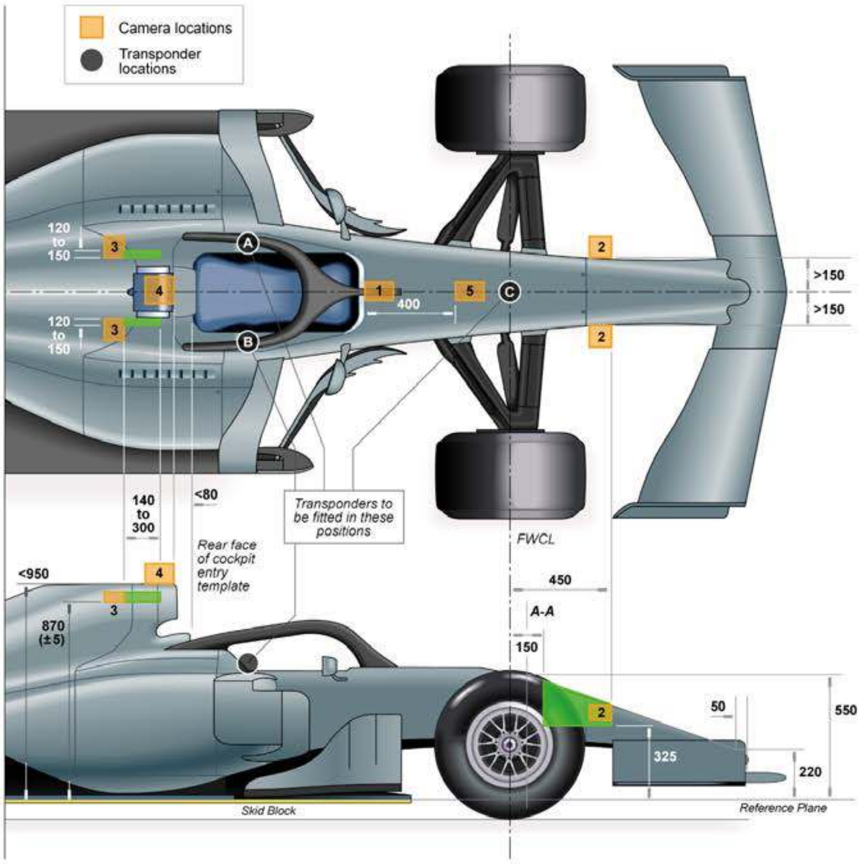
says. 'There was a general consensus that because development had been underway, we were dealing with a wing that fits a particular box and the fact that it shoots up by 50mm isn't a game-changer.'

Aero-elasticity (flexible bodywork) remains very much on the FIA's radar for 2019, though there is a little more give allowed in the rules for the rear wing. The new regulations allow for 3mm deflection under a 500N downward load where only 2mm was permitted in 2018, but this increase is due to the increased width of the wing. It is the same case with the 500N horizontal rearward load test (regularly performed at races), with 7mm deflection allowed, up from 5mm. However, while that extra allowance is to accommodate the increased span of the wings, other areas of the car, including the floor, will be subjected to asymmetric testing, with parts on one side of the car only, now able to be tested, where previously equal loads were applied to both sides of the car at the same time.

Other changes have been made at the rear with the maximum overhang extended

'We're probably going to have to wait until 2021 to see what the full package can deliver'

by 100mm (to 810mm). Also, rear impact structure length is now limited to 710mm behind the centreline of the rear wheels.



There are more camera positions on the car for 2019 and it's possible that teams will look for aero gains here

Camera focus

The number of mandatory television camera mountings will increase in 2019, with locations on the Halo and the top of the monocoque ahead of the driver. These new housings will join the existing mounting points either side of the nose and on top of and either side of the roll hoop. Camera position has in the past been used to get an aero advantage with Ferrari finding small gains in the '90s and more recently Red Bull exploiting a loophole by mounting the nose camera inside the nose. It will be interesting to see if any teams manage to make gains with the new camera mounts.

But even with the new cameras offering fresh views of the action for fans, it remains to be seen if the new rules will achieve what they set out to; improve the show as much as possible before the full fruits of Liberty's project to re-invent Formula 1 appear in 2021. Indeed, despite the rule changes being finalised there is still some scepticism in the paddock about the 2019 regulations, with some claiming that they will not make any difference at all in terms of their stated aims. 'Apparently the rules should make overtaking easier, we were sold them with a promise of a fantastic race in Australia next year,' Guenther Steiner, Haas team principal says. 'It will not be like that, the silver bullet will not work. I would love to be proven wrong, but I said from the beginning that in Australia it is just difficult to overtake, and nothing will change in 2019. Maybe we should take the wings completely off the cars and then they can overtake?'

The minimum weight has been increased by 7kg to 740kg, making 2019's racers the heaviest F1 cars ever

In fact, there is significant talk, as there was ahead of the 2017 season, that simulations done by teams suggest that the downforce reduction that should come from the new rules has already been mitigated. 'I think we're all a little bit tentative about exactly what it's going to look like,' says Jock Clear, senior performance engineer at Ferrari. 'We're going to have to wait until next year to actually see what the implications are, because of course 10 teams will come up with 10 solutions, some of which we won't even have thought about and then that may well move the goalposts slightly. We are looking at the fact that close racing doesn't necessarily mean everybody can overtake easily but it does mean that cars can follow each other and they can pressure each other. That's the thing we are targeting'

For Chester the 2019 package is more of a step towards 2021. 'Obviously, in one year you could not do all of the changes which are planned for 2021,' he says. 'But from what we've seen so far I think the 2019 rules will make a small difference. It'll go in the right direction, so the following [one racecar behind another] will be a little bit improved, but we are probably going to have to wait until 2021 to see what the full package can deliver.'

Absolute power

With 10,000bhp engines and speeds in excess of 330mph drag racing is the fastest motorsport on the planet. But these impressive numbers also means it presents one of the biggest engineering challenges in the business. *Racecar* investigates

By GEMMA HATTON

Photos: Santa Pod Raceway

The dynamics of making cars go fast round tracks has kept engineers busy for many years. Complex suspension systems have had to be designed to control the grip while the car undergoes roll and yaw during lateral accelerations. Differentials have been invented to allow the wheels on an axle travel around a corner without slipping. And aerodynamics have been modified to cope with cross-flows. Engineering the optimum set-up for a corner is hard, so surely racing in a straight line is easier? Wrong. As modern dragsters prove, racing down a drag strip comes with a host of problems, particularly at 330mph.

Santa Pod Raceway in Bedfordshire was Europe's first permanent drag strip. It hosts

A Top Fuel dragster packs more power than the first four rows of cars at the Indianapolis 500. This is the fastest category in drag racing, covering 1000ft in around 3.7 seconds the fastest and loudest form of motorsport on the planet and for a first timer it is all very impressive. As are the numbers. The fastest category of dragster is Top Fuel and these 10,000bhp beasts race 1000ft (305m) in 3.7seconds, at speeds of over 330mph, which means they accelerate at 100mph per second.

Daze of thunder

The power produced from one Top Fuel engine is more than the first four rows of the Indy 500. The explosive launch off the start-line exceeds 5*g* and the shockwaves as these racers punch this monumental amount of power into the track rattles your skeleton, blasts your eardrums and even sets off all the car alarms in the car park. There is truly nothing else like it.

The Top Fuel dragsters run a supercharged and fuel-injected 8.2-litre, 426 Chrysler Hemi based all-aluminium V8 powerplant that is powered by nitromethane fuel. The chassis is made up of a chromoly steel tubular spaceframe with carbon-fibre panels and the cars are 7.62m long and weigh 1057kg.

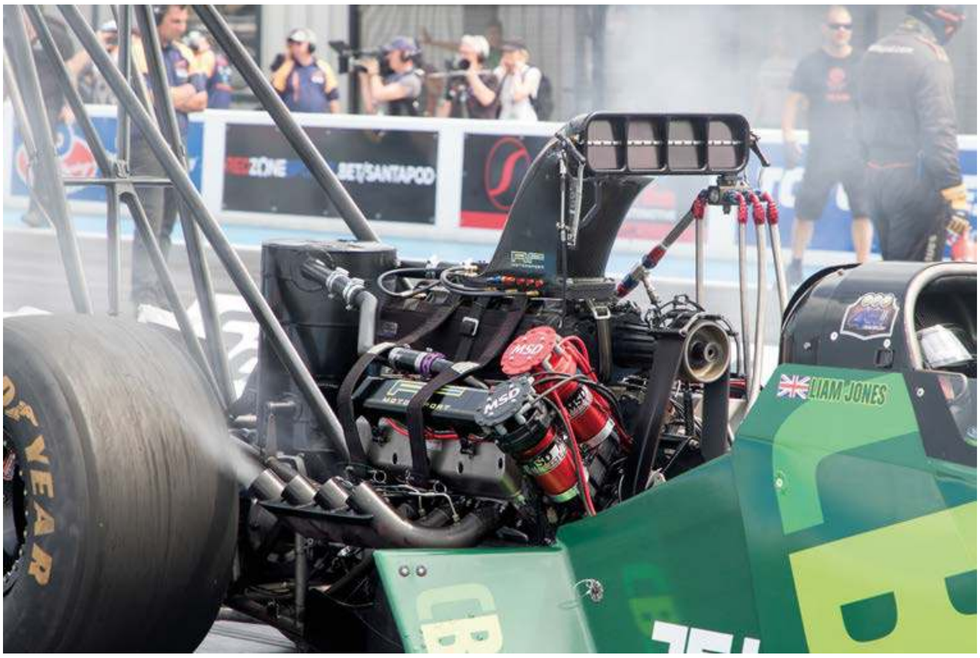
The second fastest dragster is the Funny Car, which can get to the end of the drag strip in under 3.8 seconds. These racecars use the same supercharged engines and are very similar to the Top Fuel cars, apart from a shorter wheelbase and a carbon-fibre body that loosely resembles a production-based car.

Then there is a whole array of categories ranging from Super Stock, which are modified passenger vehicles, to Pro Mod, which are the fastest saloon cars in the world. Each class is defined by its own set of regulations and each dragster is as wacky as the next.

But it's the faster cars that are the most interesting. Just how do these generate, utilise and control that astonishing amount of power to achieve 330mph in under four seconds?

Special brew

First, you need to generate power and for that you need fuel. Both the Top Fuel and Funny Cars run with nitromethane, while other categories such as Pro Mod run with either supercharged methanol, turbocharged methanol or nitrous oxide injection. Nitromethane is capable of generating 2.3 times the amount of power that a gasoline equivalent engine can. Its chemical formula is CH_3NO_2 and because part of the oxygen needed to burn is actually carried within the molecular structure of the fuel itself less atmospheric oxygen is required, resulting in typical air fuel ratios of 1.7:1. Teams are regulated to running 90 per cent nitromethane with 10 per cent methanol and the fuel is delivered by two fuel pumps which are attached to the camshaft, so as the camshaft spins round, it rotates the pumps. This then brings fuel up to the inlet manifold which distributes the fuel to the 42 fuel injectors. Astonishingly, the pumps are capable of delivering more than one gallon of nitromethane per second in Top Fuel



To help generate 10,000bhp Top Fuel cars run a supercharger which is capable of adding 57psi of boost into each cylinder

Dragsters 'burnout' on the start-line to warm the tyres and put down a layer of rubber for extra grip at the start

The engines are so powerful that they can destroy themselves in a single run

cars, which is the same rate as that of an engine on a passenger jet such as the Boeing 747.

To ignite the fuel, two spark plugs along with two magnetos are used per cylinder in Top Fuel. Magnetos are small electric generators that supply 44 amps to each spark plug, which is a similar output to an arc welder. The power of the engines is such that they can destroy themselves in a single run. The spark plugs wear away, while the connecting rods, pistons, rings and bearings all have to be checked as part of a full engine rebuild after each run.

The combustion chambers are hemispherical where the top of the cylinders are a dome shape as opposed to being flat. This maximises the volume of the combustion chamber while decreasing the surface area and therefore reducing heat loss, allowing for that heat to generate more power during the combustion process. The valves are in a crossflow design, where the intake and exhaust valves are located on opposite sides of the cylinder head, to allow for a straight flow path of the charge air volume in and out of the combustion chamber.

Pump action

'In Pro Mod, we actually use a fuel flow meter to monitor exactly how much fuel is going into the engine and then we analyse the data to determine if we are running too rich or

too lean,' says Andy Robinson, owner of Andy Robinson Racecars and seven-time MSA British Drag Racing Champion. 'We run a very basic fuel injection system which is quite archaic. It is mechanical and based on poppet valves and returns the fuel back to the tank. So the more fuel we return from the pump to the tank, the less that goes into the engine. Therefore, if we use a bigger fuel jet it will actually lean the engine rather than making it richer. But we fine-tune this with four solenoids that are controlled by a timer system so we can trim our fuel curve if we are running too rich at any part down the track. When the car is at the eighth-mile point, we put most of the fuel back in again because it cools down the engine to stop detonation. We also play with the timing, so we have 28-degree of timing in the motor but we pull this out at the start-line to help put the power down, and then we ramp it back in during the run.'

In addition to the monumental amounts of fuel guzzled by Top Fuel dragsters, a supercharger is also used to provide an extra 57psi of boost into each cylinder. Typically, Roots superchargers, or blowers, are used, where two rotors with three lobes rotate, creating pockets of air between the lobes and the case as the air is moved from the intake to the discharge side of the lobe. The rotors move more air than the motor can ingest; generating boost.

Direct drive

Unlike other racecars, this power from the engine is not transmitted to the wheels via gears and a transmission. Instead, a centrifugal clutch is used which consists of five sintered iron discs and four floaters that are clamped together by levers. This provides direct drive of the torque and energy from the engine to the rear axle.

Once the torque has been transferred to the rear axle, it is then the job of the tyres to translate that into grip and speed. To achieve this, the coefficient of friction between the tyres and the track must be maximised. This is why the tyres are such a soft compound and the drivers complete burnouts to add a layer of rubber to the track. Top Fuel dragsters, Funny Cars and Pro Mod run 36in diameter tyres at the rear. These rear tyres are a very soft compound with extremely thin sidewalls. Under launch, this allows the tyres to wrinkle and squish into the track, increasing the contact path area and therefore grip. However, during the run the huge amount of centrifugal force within the tyre actually forces the outer walls of the tyre outwards, resulting in the original 36in diameter tyre actually expanding to 44in tall, which has the same effect as shifting up the gears.

The biggest threat to drag racers though, is tyre shake. 'This is when the tyres run at very low pressure and the rubber will essentially 'wad up' and create a crease in the tyre. Once the wheel runs over that crease, the tyre will instantly lose traction and then gain traction,' explains Neale Saunders, project manager at Santa Pod Raceway. 'This process repeats and it results in such violent vibrations that it can damage the car and I have known drivers who have chipped teeth or blacked out because of it.'

'You can't really manage tyre shake,' says Anita Makela, FIA European Top Fuel Champion in 2018 and 2016. 'In qualifying you just try to run as fast as possible to get a good qualifying position. So if I get tyre shake and lose traction I just lift the pedal because there is no point because the time will be bad. But when you get to the elimination rounds you have to step back on the pedal to get some kind of grip to try and get over the finish line before the other car because you never know where they are.'

The runs starts with the tyres slipping and deforming dramatically. This increases the contact area of the tyre on the strip

The astonishing rate of fuel burn hugely affects the weight distribution throughout the run

The driver's view

What's it like to drive a Top Fuel car? 'It's hard to put into words how I'm feeling when I am accelerating from zero to 100km/h in less than half a second,' says Anita Makela. 'It's you who has to control the speed of the car, not the other way around, the car doesn't take control of you, but of course it's not the 300mph-plus top speed that is dangerous – it's the sudden stop if something goes wrong. But I don't even think about that.'

The thrill of drag racing lies within those big top speeds, which means that both the driver and the car all have to perform instantaneously, and operate correctly. Unlike circuit racing where a mistake during a lap doesn't necessarily mean your race is over, a mistake during a drag race run can effectively end your weekend, in more ways than one.

'Obviously, you are always trying to beat the car that is racing you, but by making the best out of your own run. Because the cockpit has such high walls, you cannot actually see the other car unless they are really ahead of you, so I just focus on myself,' says Makela.

To set themselves up for the run, the first thing the drivers have to do is find neutral while their crew start the engine and adjust the fuel. The driver then releases the brake and slowly rolls forwards to where they will then complete a burn out to lay down a layer of rubber on the start-line, as well as warm the gigantic rear tyres. The driver then reverses and the crew chief will guide them on to the rubber tracks they just made and they move towards the start-line. The driver then moves forward into 'pre-stage', closes the windshield, opens the fuel, clutch off, and holds the brake pedal, moving further forward into 'stage', which triggers lights to indicate that they are ready to race.

When the lights go green, the driver accelerates off the line, trying to manage any tyre spin and steer the dragster in a straight line. As soon as they see the finish line they release the parachutes and lift off the pedal and the only way to shut down the engine is by cutting the fuel flow.

One of the most impressive, though mainly unsung, aspects of drag racing is the high number of females who are involved either as mechanics, engineers, or drivers. In fact, for a few weeks in 2018 there was a female champion in all three major Top Fuel drag racing championships worldwide: Brittany Force was the 2017 NHRA Top Fuel Dragster champion, Kelly Bettes claimed the 400 Thunder Top Fuel title in Australia and Anita Makela won the FIA European Top Fuel Dragster championship. 'There are no gender issues in drag racing,' says Makela. 'When you put the helmet on it doesn't matter whether you are male or female. In Top Fuel all that matters is how fast you are and how skilled you are at controlling that amount of acceleration.'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While combating drag is the name of the game, with so much power on tap a huge and very high rear wing is required. The more modest front wing is there to stabilise the dragster

Despite being in the title of the sport, drag is actually the enemy of any dragster, simply because it will slow the car down as it powers up the strip. Therefore, while you may have thought that downforce is not so important in drag racing, aerodynamics actually provide an essential force in keeping these rockets in all but name on the ground. Top Fuel racers have gigantic rear wings that can generate up to 8000lb (35.6kN) of downforce and a more modest front wing capable of 700lb (3.1kN), which is intended to stabilise the car.

Wheely useful

In Pro Mod, wheely bars are often used to stop the dragster from flipping over, instead of wings. 'We even use pressure sensors so that we know how much load we are putting into the wheely bars so that we can adjust the set-up if necessary,' says Robinson. 'The whole point is that if we can get the car to leave the start-line with perhaps 40 or 50mm under the front tyres, the car will travel dead straight, which is the quickest way down the race track.'

In terms of weight distribution, the fuel tank in Top Fuel is in the front of the racecar and, therefore, the astonishing rate of fuel burn hugely affects the weight distribution throughout the run. The weight distribution is a consideration in the other categories, too.

'In Pro Mod we run slightly more front weight than rear because the cars are so aggressive,' says Robinson. 'On our earlier racecars, we actually used to move the engine rearwards to get enough weight over the rear axle, but we now have so much torque and power from the engines we're using that we don't need to do that anymore.'

To help guide the car straight, the load on the rear tyres needs to be identical. However, with the huge forces and torque generated by the engine, to achieve this during the run the rear wheels actually start off with different loads. 'Every action has a reaction so what we try to do is put a certain amount of weight on the tyre, so as the engine rotates one way, it will twist the axle that way, then there is a reaction on the chassis which twists it the opposite way,' highlights Robinson. 'On this racecar we run an extra 20kg on the rear left tyre due to these reactions. The engine will put more weight on the rear left, but the reaction of the chassis rotation will take it all off, so we try to have the same amount of weight on both the rear tyres to ensure that the car will go dead straight.'

Adding to the complexity of this vehicle dynamics conundrum, drag racers also often use rear steer. This is where the rear axle is deliberately skewed and, in Robinson's case, the right hand side is 3mm forwards compared to the left. 'Everything is trying to push the car to the left and we are trying to correct that to keep the car straight. So when you see a dragster going down the drag strip completely straight it is down to a good set-up.'

Top Fuel dragsters have gigantic rear wings that can generate up to 8000lb of downforce

With 10,000bhp launching the tyres off the start-line you may wonder how on earth you design a track surface to cope with such shock loading. Santa Pod Raceway had to engineer a solution to this problem as it resurfaced its strip for the 2018 season. 'We used a very hard concrete mix, FC50 XF, which is almost unheard of in the industry, and is new for us as our previous surface was tarmac,' explains Saunders. 'Concrete is a very tight surface with no holes, whereas tarmac often consists of many pores. This means that the tyre footprint is in complete contact with the track compared to tarmac, where the area of all those pores adds up and means you can't put as much horsepower into the track. Also, a tarmac surface, particularly on a hot day, becomes more malleable and so when a huge amount of power is interjected into the track through the tyres, the tarmac actually absorbs some of that power. Whereas concrete essentially reflects that power.'

Strip show

The construction process began by digging 800mm down into the ground, removing the old track, the old World War II concrete runway and the rough foundations underneath. After removing the old strip, compaction tests were carried out on the clay sub-base and the poor results meant that 5000 tonnes of unsuitable

Some 11,000 tonnes of stone and crushed concrete were used to build the new concrete strip at Santa Pod Raceway. Achieving a high-performing surface in the depths of a UK winter proved to be an engineering challenge

‘Around 80 per cent of the work on this track can’t be seen – it has all taken place underground’

Pro Mods are said to be the world’s fastest saloons. Their rear axles are skewed to compensate for the huge chassis torques

clay material had to be removed to reveal a firmer material underneath. Once this material satisfied the compaction tests, the foundations were then built using 4000 tonnes of crushed up concrete from the old Second World War runway. The total 11,000 tonnes of stone and crushed concrete sits on top of a geogrid steel mesh and a drainage network made up of drainage channels, equating to 1.5km in all. The geogrid supports the track by spreading the loads and stops any part of the track collapsing or dipping into the soft undersoil.

‘Around 80 per cent of the work on this track can’t be seen – it’s all taken place underground in the drainage and foundations,’ says Saunders. ‘Of course, our biggest challenge was with the UK climate and due to our busy schedule we did not have the luxury of laying a new track in summer, and so our only option was to resurface in the winter.’

Santa Pod used a state of the art laser screed machine, which essentially used lasers to level the material to extremely high accuracies. Unfortunately, for this to work effectively the windspeed had to be low to avoid disturbing the lasers. Furthermore, to achieve a smooth surface finish, there had to be no rain and the ambient temperatures had to be above 5degC to ensure the concrete cured at the desired rate.

‘It is hard enough to get those three combinations on the same day in the year, let alone during the winter,’ explains Saunders. ‘So we got everything ready and as soon as we had a suitable weather window that met the criteria, everyone swung into action and worked solidly.’

Flat chat

The concrete was laid in 88m sections with expansion joints at each end and a construction dowel joint at 44m. The topography provided yet another challenge; the finish line is actually 1.3m higher than the start-line, so although it is not noticeable the track does go slightly uphill. There is also a 50mm height difference from each side of the track to the centre intended to help with drainage, to avoid standing water. However, despite these various tilts, the track is completely flat to within +/-2mm.

‘We have almost made the track too good,’ says Saunders. ‘Every high horsepower car needs to turn the tyre as they leave the start-line. This is where the tyre needs to slip a tiny amount, as soon as the driver hits the throttle, so the surface needs to have a bit of give. But our start-line is now so grippy that a lot of the big cars are struggling to turn the tyre, and that can lead to tyre shake. Essentially the cars cannot produce enough horsepower to be able to slip the tyre on the start line with our grippy surface. We need to go away and decide if we retain the aggressiveness of our track.’

Restore de force

Modern-era grand prix cars are notoriously difficult to rebuild and to maintain, yet one group of former F1 engineers have banded together to form a company that does exactly that. *Racecar* paid Tour De Force a visit to find out more

By SAM COLLINS

On a former Cold War airfield about an hour north of London lies a building packed full of grand prix cars from the past 20 years, most of them in varying states of deconstruction. This is the home of Tour De Force, an engineering company specialising in the rebuilding and maintenance of modern Formula 1 cars; though this description rather understates what it does.

'We like to think we are perceived as being the engineering A-Team, if there is a weird and wonderful problem with no obvious solution they call us to help solve it,' says company founder and managing director Matt Faulks.

Faulks, like all of Tour De Force's seven full time staff, started his career working for a Formula 1 team but felt that the opportunities in the sport were too restricted. 'Just under a decade ago I was working for a team on engines and gearboxes and I really started to miss being involved in whole car projects,' he says. 'I realised that the further you get into F1 as a career the less of the car you get to tinker with. You get pigeon-holed into an area, and while it may be an area you are extremely good at you end up losing visibility of the rest of the car. For me the whole-car engineering aspect has always been incredibly interesting and that was part of the driver for setting up the company.'

Starting out

But when Faulks made a decision to leave Formula 1 he did not intend on immediately setting up what became Tour De Force. 'About 10 years ago I was offered the chance to go to Cologne to work for Toyota,' he says. 'I looked at it, but felt that it was not really for me, I didn't want to be working in Germany as I would be so far away from Motorsport Valley. In Britain there was a lot of stuff going on that I could get my teeth into at the time. So I decided to take six months off, away from F1, and decide what to do next. I managed about three days off. I got a phone call about an old Minardi that the owner wanted to get back on track and was asked to help. That was the start of the company.'

Today Tour De Force has outgrown its original premises and relocated to a larger facility at Bedford Autodrome, yet even now it is still expanding and the workshop is constantly full of ongoing projects. 'We have always been very quiet about what we do, we have really just grown organically, with people hearing of us by word of mouth,' Faulks says. 'The world of private Formula 1 car ownership is really just a very small village, so when a car appears on track in private hands that nobody thought would ever work again other owners ask where they got the work done, and that is how we have grown. We have global business now, we have customers from right across Europe, the USA, Australia and Singapore. In terms of cars we have an involvement in it is around 80 globally.'

While maintaining and operating modern F1 cars is not unique, with the likes of Williams Heritage and Ferrari Corse Clienti offering a similar service for cars those outfits have produced in the past, Tour De Force has no ties to any particular team or manufacturer and

A Sauber in unfamiliar colours. Tour De Force restores F1 cars to order, so they are not necessarily always historically accurate

'As the staff is made up of former Formula 1 people we have a lot of contacts as a company, and that gives us the ability to speak to the right people'

simply works on what comes in. A number of cars from the Minardi team were the first, followed by a range of different makes and models, not all of which the company has revealed. Cars from Benetton, Jordan, BAR-Honda, Ferrari, Jaguar, Virgin, Lotus, Caterham, Renault and Sauber are all known to have passed through the Tour De Force facility.

Going cheap

Old F1 cars can actually be sourced surprisingly cheaply, often for less than an entry level Ferrari road car, but the price of these cars is low because they need a lot of work before they can return to the track. 'Mostly we try to work with modern cars, so from 2000 onwards, though we have worked on cars from the mid and late 1990s, Faulks says. 'So most of our work is 1995 onwards with the bulk of it post 2000. We really want to get the most modern cars possible. Right now we are heavily involved with 2010, '11, and '12 cars. We have a good reputation for running the V10 era cars too and we have really created a bit of a niche for ourselves as before we did it the general perception was that it was impossible to run them.'

One of the reasons that modern F1 cars are considered too hard for private teams and owners to run is that they are incredibly complex, and outside of the confines of the teams which built them (many of which no longer exist) there are almost no drawings or data to work with. This means that a lot of detective work has to be done.

'As the staff is made up of former Formula 1 people we have a lot of contacts as a company, and that gives us the ability to speak to the right people, or at least people who know the right people,' Faulks says. 'So let's say we had a Toyota F1 car come in. My first port of call would be Gian Carlo Minardi. That is because the chap [Gustav Brunner] who was the technical director at Toyota, had also been the technical director at Minardi until 2001, so they know one another well. I would then get his contact details and work from that.'

Knowledge gaps

However, even if the team already has the right person's contact details that may not be enough as sometimes the data for the cars simply no longer exists. 'If, for whatever reason, we can't contact the right person or the information simply is not available we look at other options,' Faulks says. 'We do this pretty much constantly as with all of these cars there is always something we have to re-engineer or there is something missing. So we have to design it and make it. I think that's what makes us a unique company, we are a small company but we have full time designers, our own machine shop and build areas. There is a lot of synergy between

It might have Honda on the rear wing but this is actually a rather rare BAR-Cosworth. This proved to be a challenge for the TDF team, which had to change the rear of the bulkhead

'There is a lot of synergy between what we do and what a Formula 1 team does, we are just on a much smaller scale'

Engines such as the Honda V10 are impossible to source so other options often need to be found

what we do and what an F1 team does, we are just on a much smaller scale, but we don't lack any capability compared to an F1 team. The only real difference is that we are not producing things at the same rate they are.'

Indeed, the capabilities of the company are such that there are rumours that it has ongoing projects with current F1 teams, though Faulks prefers not to go into too much detail. 'We work very closely with Haas on a lot of our machining requirements, we also have some work with Haas F1 on a few interesting bits and bobs,' he says. 'We have also done some very interesting bits and bobs over the years including Le Mans cars, we get a lot of different work depending on the varying requirements of the teams.'

Rolling stock

Often, old Formula 1 cars are sold as rolling chassis, without engines or complete gearboxes and usually they are missing other major parts too. 'If you look at a Honda-powered car a lot of the kit no longer exists, its just not out there anymore,' Faulks says. 'So at that point you have to look at other options. We had an ex-Jenson Button BAR 006 in but there was just no way of getting hold of a Honda V10. So we decided to install a Cosworth V10 instead. But rather than just tack it on the back of the chassis with a bit of hose we did it as a proper integrated item. That meant changing the rear of the bulkhead in exactly the same way as Brawn did in 2009 to switch from Honda to Mercedes. We have followed the very same process.

'We then looked at the electronics and opted to use Magneti Marelli rather than Delphi as it is far more accessible and we already had a set for it to use with the Cosworth V10,' Faulks adds. 'We did our own gearbox control on that as well, though it remains fully hydraulic as it was on the original car. We essentially re-manufactured that BAR-Honda into a BAR-Cosworth.'

Sourcing differing engines for Formula 1 racecars is not a major headache for the 3-litre era cars, so long as the owner is willing to switch to a Cosworth or Judd V10, as both are available. However, if the owner wants the car to run with the original engine then electronic systems can cause a headache. A Formula 1 car built in the mid 1990s may well need software from the same time period to operate it.

Cars often arrive in an incomplete state but the company can always find or fabricate replacement parts

If the owner wants to retain the original engine then the electronic systems can cause a bit of a headache

'There are two ways of doing it,' Faulks says. 'The first option is to create a virtual machine using emulator software and that works in a lot of cases. In other cases we simply have to use old hardware so we do have some old laptops and cables on the shelf for that reason. The only one which can be tricky is McLaren, which built stuff into its hardware which is proprietary.'

In fact, in the Tour de Force workshop is what may well be the last operational Magneti Marelli STEP F1 electronics lab with support for STEP6 and STEP8 F1 electronics. But while using a computer from the correct period to run a car might have a certain appeal to an owner at historic events, it is often not exactly practical. So in many cases the cars get a software update.


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'With one 1995 Jordan we were working on we had to create an entirely new gearbox within the original transmission casing'

'It depends on the owner,' Faulks says. 'It is sometimes the case that they want to move to more modern kit anyway. If they do we have the ability to use a modern ECU to run the car. We work quite closely with Life Racing and we can get the chassis controllers and engines to work with their hardware, but it can be a lot of work on the computer. There is a lot of reverse engineering we have to do. We do have good relationships with Shiftec too, and that allows us to develop our own code for their controllers and things like that. We can do a lot on that side of things, being able to run systems which have not existed for a number of years.'

In some ways transmissions can be harder to deal with than engines for private F1 car owners as V10 F1 engines are available from Cosworth and Judd while gearboxes are generally bespoke; and as a fully stressed part simply changing to a more readily available transmission is not really an option.

'It's what can make the cars very tough,' Faulks says. 'With some of the Minardi cars we would run into issues where the parts we needed didn't exist anywhere, there were not even old ones we could copy. So we ended up having to do things like manufacturing completely new differential assemblies with no information at all beyond the shape of the hole in the gearbox casing to go on.

'On a 1995 Jordan we worked on we had to create an entirely new gearbox, which itself is a challenge, but on this one we had to do it entirely within the original gearbox casing,' Faulks adds. 'It was just an empty casing with a front cover. So we created a complete new transmission inside that casing, new shafts, selectors, gear ratios everything. We had to work really closely with Elite to get that done. That really was a tricky one.'

Titanium issues

Even if all the parts of the car are present they may not be safe to use on track, after all in most cases the transmissions were designed to last a few races at most and no attention was paid to what they might be like years later. 'You might think that composite gearboxes would be a big issue, but they are not really that bad as you can glue them back together again,' Faulks says. 'Instead, what we have found is that you find the biggest issues with some of the rapid cast titanium casings from around 2004 to 2006. You often find issues with porosity with those, and as the castings are quite thin you can see crack propagators. They can become irreparable quite easily and in that situation you have no option other than to make a replacement. Luckily, with those the process used to make them is still

Tour De Force also provides support to help run modern-era Formula 1 cars, such as this Sauber, at the track

available as it is essentially 3D printing, and CRP in Italy are able to do that for us really well.'

There is actually no real convention as to what happens to old Formula 1 cars at the end of a busy season. Some end up serving time on test rigs, while others get turned into simulators. Others are stripped down and placed in storage indefinitely, while a few are used as show cars. With such uncertain histories each car that comes to Tour De Force is subjected to extensive testing.

'We have a very aggressive NDT [non-destructive testing] process, everything which comes out of these doors has been through that,' Faulks says. 'One of the first things we do when we get a new car in is strip it and send everything off for NDT. Then we make the decision to make or replace parts, and for the parts we don't feel we need to replace we work out inspection intervals. We create a full programme for each car detailing inspection intervals for each part and the life of some parts; when they need to be replaced.'

'We create a full programme for each Formula 1 car, detailing the inspection intervals for every part'

Some parts almost always need replacing, either through wear or simply from not being available anymore. 'Dampers are hard to source so generally we have to make them ourselves,' Faulks says. 'If we get complete units we can look at using them but usually they have missing or broken parts so we still have to make the missing bits, you can't exactly order a spares kit for a Formula 1 damper. Our first process is always to rebuild what is there if it is possible, if that is not possible we will work on creating new ones. We work with Quantum and Dynamic, too, to get parts done.'

Beyond Formula 1

Tour De Force also conducts work outside of the renovation and maintenance of historic F1 cars, but even on those projects it aims to inject more than a little bit of grand prix racing knowledge. 'Outside of Formula 1 in general we use the same approach and technology that we do with F1 projects, and we can help bring that Formula 1 way of doing things to these other projects,' Faulks says. 'We were very heavily involved with the BAC Mono single seater road car for example. We did a lot of the electrical work on that and the powertrain integration and helped them get that car from a CAD model to a produceable product.'

With Formula 1 teams today only building three or four chassis a year it seems likely that the scarcity of modern F1 cars will increase. But for decades teams would build six to nine cars a season, which means that there are still more than enough F1 cars out there to keep Tour De Force busy in the years to come.


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Sorting the rough from the smooth with your drivers

In a brand new series of technical insights OptimumG president Claude Rouelle focuses on a race driver's key performance indicators – kicking off with steering wheel smoothness

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

Just how do you measure, compare and improve racing drivers? In this new series we will be addressing that very question; looking at driving style and how this relates to driver performance. This first article will discuss the drivers' steering wheel smoothness, and our first stop is with the data acquisition.

The way in which a driver works the wheel will tell you much about both the driver and the racecar

Data acquisition

A vehicle's data acquisition system is composed of an electronic memory device that stores values measured from the vehicle's sensors as a function of time. The data acquired can then be processed for further analysis.

The data collected can be divided into three main categories: the vehicle's vital signals, vehicle performance, and driver performance. The vehicle's vital signals are all the channels related to reliability. The channels that are typically included are: engine oil pressure and temperature, water temperature, fuel pressure, gearbox and differential temperature, battery voltage, engine rpm, lambda, exhaust gas temperature, etc.

Vehicle performance channels are parameters that are vehicle dynamics related, channels such as: vehicle speed, accelerations, damper position, tyre temperature and pressure, ride height, suspension loads, tyre loads, side slip angle, yaw velocity, engine speed, etc.

Driver performance channels are parameters that the driver controls, such as throttle, brake and steering position, and gear position.

The vehicle vital signals are the most important and should be checked first before making any additional analysis. Driver performance channels can tell us how the driver is performing on track. Vehicle performance channels help us understand what the vehicle is doing with the different set-up changes. But the biggest challenge for any data acquisition engineer is how to process all this data in the minimum amount of time.

Measuring up

Key performance indicators (KPIs) help achieve this objective as they represent a type of performance measurement. These metrics can be the maximum, minimum, average, deviation, etc., of a channel.

KPIs allow us to reduce the amount of data and get it to the engineer so they can quickly extract and visualise mindful data, which makes it easier to interpret numbers and highlight relationships. The goal is to find patterns, optimums, predictions, deviations, etc.

Being able to process, filter, and visualise data is an essential part of data-driven engineering. It is not only about efficient analysis but also about quickly making the right decisions on the car set-up and, sometimes, to make the driver attentive to some of their driving habits that they may want to modify.

Driver performance channels are parameters the driver controls

A good data or performance acquisition engineer will first observe and compare, and then draw conclusions. It is very common for an engineer to look at the data and then immediately make a conclusion. The first question they need to ask themself is: are we looking at the cause or the effect? KPIs will help guide the data engineer to look at the right data.

The steering wheel is one of the driver controls that has a direct relationship with the heading of the vehicle. Turning the steering wheel requires the driver to have a certain amount of smoothness as to not unbalance the vehicle. How the driver reacts from the feedback given by the vehicle and steering wheel will reflect on how fast they will turn the steering wheel.

There is a strong coherence and correlation between the steering wheel angle and vehicle response. If the driver applies corrections, something is not happening as they expected, or as it should be.

In a perfect world, with a perfect vehicle, race driver, and track, the steering wheel angle, for a constant radius corner, would be the one presented in **Figure 1**.

Here the driver brakes at the ideal braking point, turns the wheel with the necessary amount of steering at the exact steering speed, generating the maximum tyre lateral force, upon

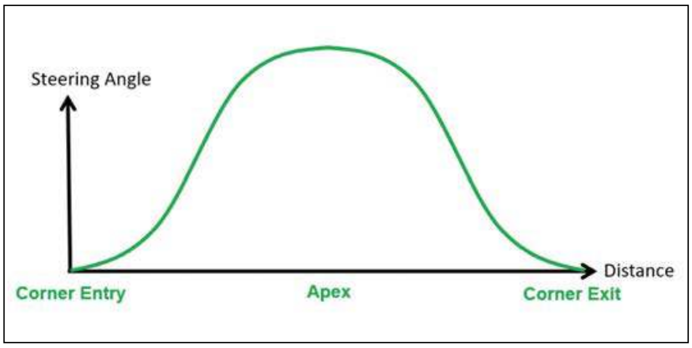

Figure 1: This shows a theoretical steering wheel signal in a perfect world

reaching the apex; no corrections or small increments of steering are necessary to have the tyres at their peak. After the apex, the driver returns to zero steering angle by applying the same amount of steering and steering speed.

Reality check

In fact, the real steering wheel angle signal doesn't correspond to the idealised signal of **Figure 1**. The signal will be fuzzy, with variation in amplitude and frequency resulting from corrections of the driver due to the track grip/bumpiness and balance changes. **Figure 2** shows the real data acquired from a steering wheel angle sensor in a corner.

This discrepancy between theory and reality is due to track irregularities, driver input, tyre wear, car balance correction etc. The only feedback that the driver has is the steering feedback given from the front wheels' self-aligning torque. Any variation of the steering wheel will provide an idea of how much grip or yaw moment is still available (that is the sensing part of the control loop driver input – car behaviour) which will cause the driver to counter steer, for example, to correct for oversteer.

By combining the idealised steering wheel angle with the actual steering angle, we can create the steering smoothness channel. This metric comes from filtering (smoothing) the raw steering wheel angle channel to obtain a smoothed steering data, as can been seen in **Figure 3**, where we are comparing the actual steering wheel angle (in red) against the steering angle smoothed (in orange).

The smoothing is done by applying mathematical filters such as a moving average or using a low pass filter. In the case of analysis software, MoTeC i2, we can filter the data by using the *Smooth* filter (see **Table 1**). This applies a moving average to our data. The user can then decide how they want to filter the data, using time or number of points.

Smooth operator

We can then calculate the steering smoothness (**Table 1**), which is the difference between the steering wheel angle and the steering wheel angle smoothed. The *abs* function is used for the case where the real steering signal is below the smoothed signal, since this would give a negative value and cancel out the positive values when calculating the average.

Additionally, for the steering smoothness KPI we are not interested if the driver is over- or under-correcting their steering. This kind of analysis is part of another KPI. The result of this operation is presented in **Figure 4**.

A handling problem will mean the driver makes more corrections

A vehicle with handling problems will require the driver to make more steering corrections. This is observed in **Figure 3** and **Figure 4**, particularly at the apex. This can be an indication that the driver is having problems with the vehicle balance mid-corner.

After calculating the steering smoothness, we can then calculate the steering smoothness KPI for each lap by calculating the average of the steering smoothness, to obtain a statistical value as a measure of the steering smoothness (**Table 1**). The lower the average value, the fewer corrections the driver applies to the steering wheel.

Using the previous defined KPI, we are now going to look at the steering smoothness of three race drivers. The data is taken from

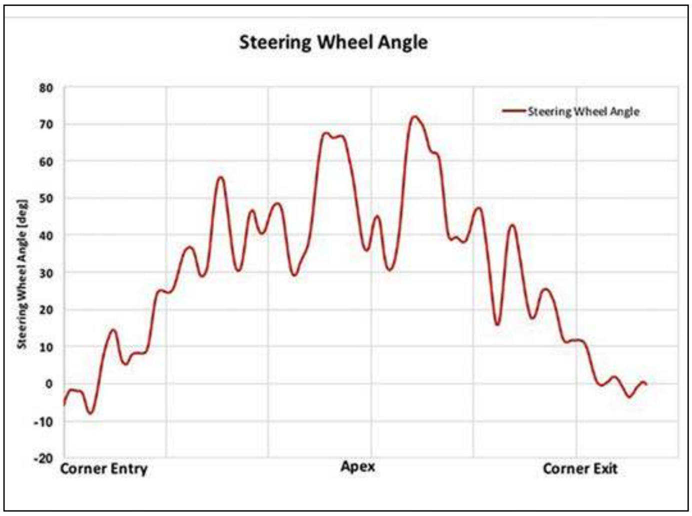

Figure 2: Real steering wheel signal acquired from an angle sensor in a turn

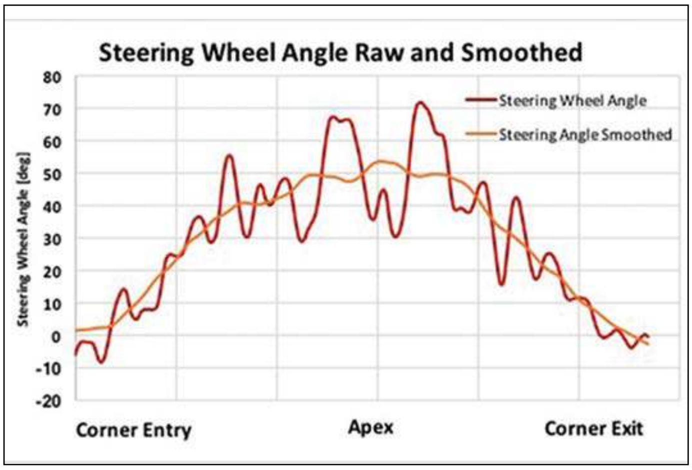

Figure 3: The original steering wheel angle alongside the smoothed angle

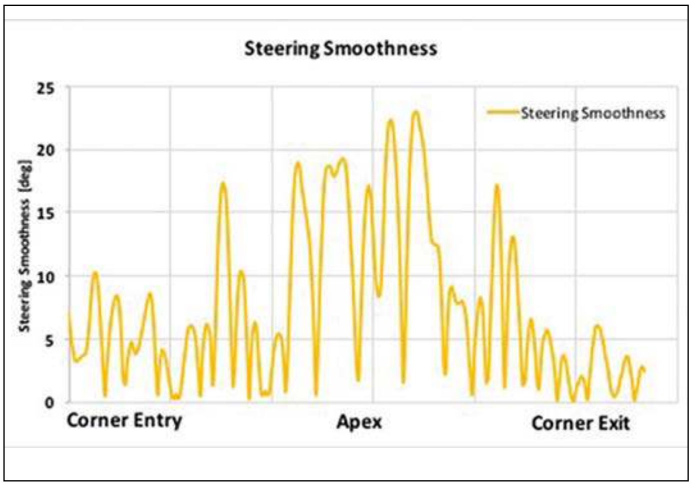

Figure 4: Steering smoothness when applied to under- or over-correction

Table 1: Math channels equations to create the steering smoothness KPI

Math channel name	Math channel equation
Steered angle smooth	smooth('Steering Wheel' [deg], 1.0)
Steering smoothness	abs('Steering Wheel' [deg] - 'Steered Angle Smooth' [deg])
Steering smoothness KPI	stat_mean('Steering Smoothness' [deg], 1, range_change("Outings:Laps"))

Efficiently being able to process, filter and visualise the data is an essential part of good data-driven race engineering

three professional drivers lapping on the same race circuit.

Figure 5 shows lap time versus the lap number. The fastest laps of each driver are respectively: Driver A, lap seven; Driver B, lap nine; and Driver C, lap six. Driver A has more consistent lap times and is normally faster than drivers B and C, even though driver B achieves the fastest lap. As the session progresses, the lap times increase for all drivers, possibly due to tyre wear.

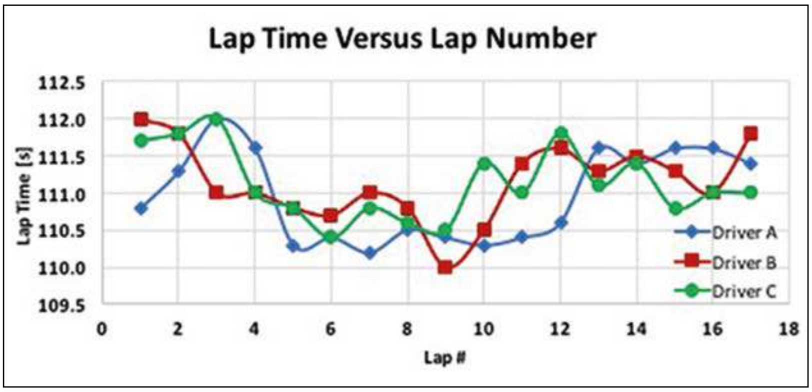

Figure 5: Lap time versus lap number for our three race drivers

Consistency

Figure 6 shows that driver A is the most consistent (less variation of the steering smoothness, which implies that there are fewer corrections of the steering wheel). Driver B and C have a higher variation of the steering smoothness, and there is a clear correlation between the lap time and the steering smoothness. The smoother both drivers are, the better the lap time. Driver A also seems to have a correlation between smoothness and lap time, but it is more difficult to see. Depending on the type of driver, there will be a stronger/weaker relationship.

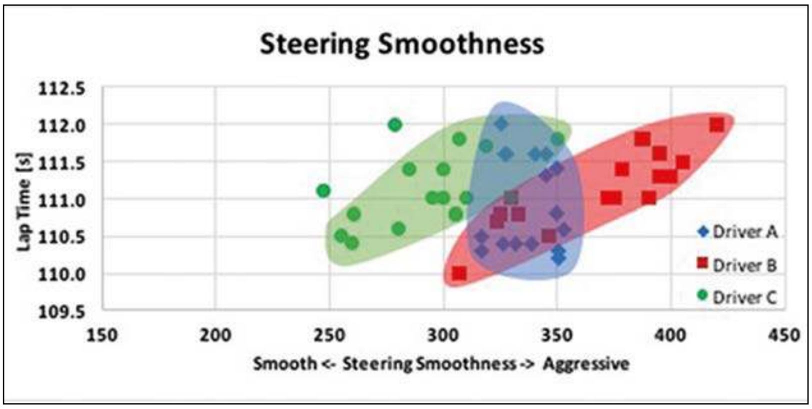

Figure 6: Steering smoothness versus lap time for our drivers

The trick is to find what works best for you and your team

Progression

Instead of displaying the steering smoothness KPI versus lap time, it can also be displayed versus the lap number (**Figure 7**).

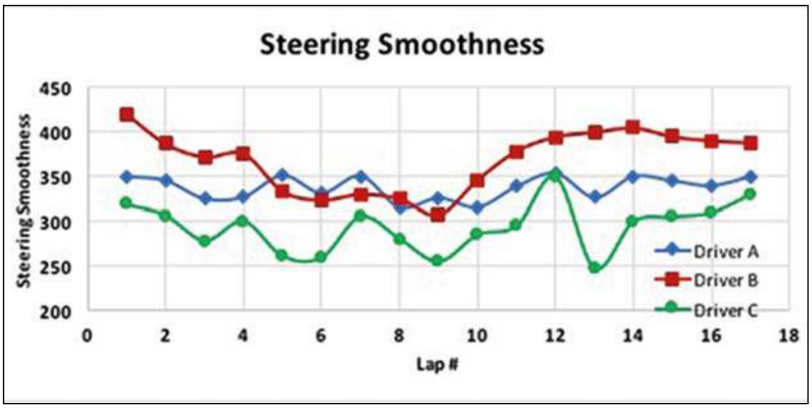

Figure 7: This shows steering smoothness versus lap number

The difference between this chart and the previous one is that we get an idea of how the steering smoothness progresses as the race session goes on. Based on this value, we could also see how the steering smoothness evolves as tyre degradation progresses.

Noticeable points are that each driver's fastest laps (Driver A, lap seven; Driver B, lap nine; and Driver C, lap six) are among the laps where the steering smoothness value is low. From the initial laps until lap nine, all of the drivers are becoming smoother, but after this, all of the drivers start to be less smooth, which could be due to tyre wear.

We must find a way to improve the speed at which we can extract the information from our data

Data Acquisition is used to monitor and better understand the data we are working with. The value is not in what is measured but in what can be done with the measured data. There are many ways to display what is measured and to obtain metrics. The trick is to find what works best for you and your team.

The steering smoothness KPI is an example of a metric that can be used to quantify the steering smoothness of the race driver. It can help the engineer to quickly identify laps or corners of interest.

A great deal of information can be extracted from time/distance charts. In a fast-paced environment, such as professional motorsport, the quick analysis and decision making is fundamental, and we must find a way to improve the speed at which we extract information from our data. KPIs automate the analysis process.

When comparing steering smoothness KPI values there will be situations where the smoothest lap does not correspond to the fastest, or there seems to be no relationship between the steering smoothness and the lap time, which was the case with driver A.

We will return to the subject of a driver's key performance indicators in future issues.

School report: Formula Student in the wind tunnel

Our new three-part Formula Student study begins with an evaluation of two very different aerodynamic approaches

Queen's University's neat Formula Student entry currently sports no front or rear wings

Visualising the flows into the 2017-spec radiator intakes on the Queen's University car

Oxford Brookes University's 2018 car featured a potent aero package developed in CFD

Here the smoke plume reveals the rear wing flow characteristics on the OBR18 FS car

Unbelievably it's four years since we visited the MIRA full-scale wind tunnel with a Formula Student car. So, partly to compensate for this long gap, we took two FS cars with us for this next mini-series.

Queen's University, Belfast, won the chance to bring its QFR18 along by virtue of winning the *Racecar Engineering* 'Engagement, Outreach and Communications' award at the 2018 UK Formula Student competition. Oxford Brookes University earned its wind tunnel place by achieving the highest position by a UK entry in the overall Silverstone-based competition in July 2018 with its OBR18. Well done to both teams. Also, the very different states of the teams' aerodynamic development enabled us to go right back to basics as well as catch up with the latest aerodynamic trends.

The QFR18 had no downforce-inducing devices at all at test time

Natural lift

As can be seen, the Queen's University car had no downforce-inducing devices at all at test time. So running QFR18 in the wind tunnel enabled us to see what the *real* baseline numbers on an FS car actually are, and by deduction and comparison with the OBR car (and previous ones tested) what are the aerodynamic contributions of the downforce inducing components. **Table 1** shows the data from the Queen's car at two different speeds (roughly 30mph and 60mph). Coefficients multiplied by frontal area have been given so that direct comparison can be made with the Oxford Brookes car.

Putting these numbers into some sort of context first, the car's CD.A value of around 0.7 is a lot higher than other non-winged single seaters we have tested (two Formula Fords for example having CD.A values of 0.428 and 0.495) and it is more akin to the Dallara F308 (2012 specification) Formula 3 car, which of course had wings and an aggressive underbody and diffuser. So it's quite a draggy car given that it has no downforce-inducing components.

Secondly, the car generated the expected positive lift but in this respect the overall CL.A value was relatively low at between 0.06 and 0.09. The Formula Fords produced 0.261 and 0.175 respectively. However, an interesting thing about QFR18 is that it generated a bigger CLAfront value at around 0.200 than did the Formula Fords (both 0.140). This may, in part, account for QFR's negative rear lift coefficient,

Table 1: Baseline data on QFR18

	CD.A	CL.A	CLfront.A	CLrear.A	%front	L/D
~14m/s	0.691	0.090	0.207	-0.117	229.9%	0.130
~26m/s	0.714	0.062	0.199	-0.137	319.5%	0.087

The University of Hertfordshire's 2013 Formula Student car ran with dual-element wings

Team Bath Racing's Formula Student car, as tested in 2014, sported triple-element wings

compared to the positive rear lift coefficients on the Formula Fords of 0.035 and 0.120. It seems likely that the front lift of QFR18, which will have developed on the convex upper surfaces of the overhung nose, and the fully exposed front tyres of course, combined with the drag moment from the tall roll hoop and upright driver, would have shifted some weight onto the back wheels. It is also possible that the slight concave upsweep on the rear of the upper sidepod surfaces was creating a genuine rear axle downforce increment.

In 2013 we tested the University of Hertfordshire's UH15 car and in one test the team removed the wings. For comparison with QFR18 those results at the same approximately 60mph speed are given in **Table 2**. There are generic similarities in the data.

Table 2: Wingless data comparison at 60mph

	CD.A	CL.A	CLfront.A	CL.rear.A	%front	L/D
UH15	0.657	0.154	0.303	-0.149	196.7%	0.234
QFR18	0.714	0.062	0.199	-0.137	319.5%	0.087

Efficient downforce

Moving on to the Oxford Brookes car, OBR18 incorporated complex front and rear wings, sidepods with well-cambered undersides and a central rear diffuser. **Table 3** shows the baseline coefficients multiplied by frontal area again, along with comparable data from QFR18 and also the Herts car (UH15) and Bath University's car (TBR14) from 2013 and 2014 respectively. Note that wheel trip strips were used to better simulate flow separation on rotating wheels.

Table 3: Oxford Brookes OBR18 data compared to other Formula Student cars previously tested by *Racecar Engineering*

	CD.A	CL.A	CLfront.A	CLrear.A	%front	L/D
QFR18	0.714	0.062	0.199	-0.137	319.5% (front lift)	0.087
UH15	1.249	-1.959	-1.150	-0.809	58.7%	-1.568
TBR14	1.597	-2.708	-1.116	-1.592	41.2%	-1.696
OBR18	1.240	-2.787	-1.313	-1.474	47.1%	-2.248

Now we can see the drag of QFR18 in a relevant context, and it's over 40 per cent lower than the UH and OBR cars, and 55 per cent lower than TBR14. This, in essence, shows the drag contribution of those aggressive downforce generating devices. The upside though is the high level of downforce these cars generate, even at relatively low speeds, and especially when compared to their weight.

Coefficients are useful for comparing data sets, but it's the forces that matter

Table 4: The vertical forces on QFR18 at different speeds

	Total lift, N	Front lift, N	Rear lift, N
~14m/s	10.8	24.9	-14.1
~26m/s	25.7	81.7	-56.0

Table 5: Downforce relative to weight on OBR18

	Total Df, %	Front Df, %	Rear Df, %
~18m/s	21.8%	23.4%	20.6%
~26m/s	46.5%	50.7%	43.3%

The patterns among the winged cars are interesting too. TBR14's downforce was created almost entirely by its potent wing package, reflected in a high –CL.A but also a high CD.A. OBR18, however, despite regulation changes limiting the wings in some respects, managed a slightly higher –CL.A than TBR14 but a drag figure on a par with UH15. In other words it generated slightly better downforce with much better efficiency than TBR14, and that has to be down at least in part to the integration of the underbody aerodynamics on OBR18.

Coefficients are useful for comparing different data sets, but it's the forces that really matter, particularly in relation to vehicle weight. QFR18 weighed in at 210kg on the wind tunnel balance (with roughly a 42 per cent front/58 rear split), which with driver would be about 280kg (616lb). **Table 4** shows the vertical forces at the two test speeds. As can be seen the forces were fairly small relative to the car's weight, and at 26m/s (58mph) front lift was around seven per cent of front axle weight (assuming weight distribution stayed the same with the driver aboard). Rear 'downforce' corresponded to about 3.5 per cent of rear axle weight. These are modest but not insignificant forces.

Examining OBR18, **Table 5** shows downforce relative to weight at two test speeds (again it was assumed driver weight was 70kg and distribution did not change from the driverless condition). Evidently OBR18 was capable of generating downforce equivalent to nearly half its own weight at less than 60mph. From this the inevitable calculation leads onto the 'Vceiling value'; the velocity at which it could be driven upside down across the ceiling – an impressively low 86mph.

CONTACT

Simon McBeath offers aerodynamic advisory services under his own brand of SM Aerotechniques – www.sm-aerotechniques.co.uk.
In these pages he uses data from MIRA to discuss common aerodynamic issues faced by racecar engineers

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Delight at the end of the tunnel

Full-scale wind tunnel testing is invaluable but it comes at a price, so you need to make sure you maximise your session time. Here *Racecar's* aero guru presents his must-read step-by-step guide on how to do just that

By SIMON McBEATH

If you were to ask any engineer involved in wind tunnel testing what are the secrets of doing it well, they will tell you it's all about preparation. Wind tunnel hire can cost thousands of dollars, pounds or euros per hour, so you really don't want to be stood looking at your car wondering what to do next. Thoughtful planning, advance manufacturing of test parts and materials, corralling the requisite tools, and organising a compact team are all tasks to do ahead of a session. The objective invariably is to evaluate as many configurations as possible in what is bound to be a limited period of time, so the way the session runs should largely be predetermined.

If you are going to a wind tunnel for the first time and you don't yet know what your racecar's aerodynamic characteristics are then some of your planning will inevitably be based on best guesswork. Even then you can at least plan for the likely contingencies. But it's always the case that you *will* be surprised at some of the results you obtain, so a degree of flexibility will always play a useful role. But we're getting ahead of ourselves here. So first, what can we expect from full-scale wind tunnel testing?

Full-scale wind tunnel testing is the only viable option for those who do not have access to a scale model of their racecar, which is to say, most of us. Full-scale testing has pros and cons; the pros include testing the actual car with all its lumps, bumps, panel gaps and other real world defects, which makes the results realistic in that sense; the substantial cost of creating a scale model and all the requisite test parts is avoided; and the problems of 'flow similarity' at reduced scale are also avoided, so the flows around real cars are representative in this sense too.

Balanced against that are some cons; some test parts will still be expensive to make at full scale; and most full-scale wind tunnels have inherent limitations including some or all of: limited maximum test speed, no moving ground, non-rotating wheels, and limited or no floor boundary layer control.

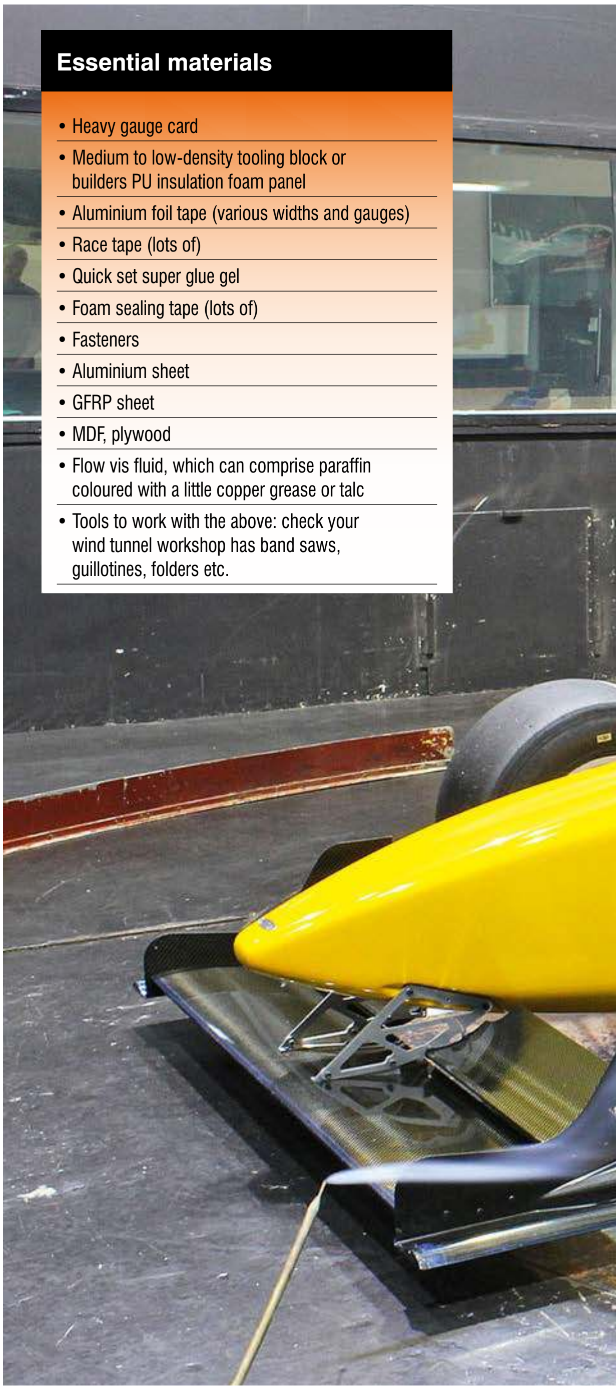
But no simulation tool is perfect and as long as the limitations of a given facility are understood then very useful indicative data and responses to configuration changes can be obtained from commercially available wind tunnels, offering as they all do controllable and consistent laboratory conditions. Such data is infinitely preferable to no data.

For the first time wind tunnel visitor, David Wain, manager at the UK's only commercially available full-scale facility at MIRA (as utilised for our monthly Aerobytes column) suggests: 'Until baseline figures are established you may not know where to concentrate your efforts. So we always suggest that new customers with no data come in for a couple of hours to measure this. After they have analysed the baseline data they can then make parts to test, and return for a development session.'

Indeed, once you know the total forces, and especially the front to rear split of vertical forces, you are in a much better position to design a programme. But it isn't always going to be viable or possible to make two visits, in which case you just have to prepare as best you can. The key is to define your objectives, prepare a plan, and gather the materials and tools you need. But before you head off to the tunnel, there's a lot more useful preparation to be done.

First, list the configurations you want to evaluate, and then prioritise them. Implicit is

Full-scale wind tunnel testing is the only viable option for those who do not have access to a scale model of their racecar



Essential materials

- Heavy gauge card
- Medium to low-density tooling block or builders PU insulation foam panel
- Aluminium foil tape (various widths and gauges)
- Race tape (lots of)
- Quick set super glue gel
- Foam sealing tape (lots of)
- Fasteners
- Aluminium sheet
- GFRP sheet
- MDF, plywood
- Flow vis fluid, which can comprise paraffin coloured with a little copper grease or talc
- Tools to work with the above: check your wind tunnel workshop has band saws, guillotines, folders etc.

that you have a clear idea of improvements you want to make (within any applicable technical regulations), be that reducing lift or increasing downforce, reducing drag, or improving aerodynamic efficiency (downforce divided by drag). Then you need to ascertain how long it takes to make each change; some, such as wing angle adjustments, can be done in a minute or two, others, such as changing a rear diffuser, can take considerably longer, and the viability and value of really time-consuming changes need careful consideration.

Once you know 'change times' you then need to add how long it takes to run each test, and you will need input from your chosen wind tunnel operator here. At MIRA, for instance, it takes a minute or two to accelerate and stabilise the wind at test speed, a minute to sample the data (two minutes if duplicate data points are used, usually a good idea) and a further minute or so to decelerate the air before it is safe to enter the test section again. So to generate duplicate data points takes five to six minutes.

Clearly then, the configuration changes will largely determine the schedule, and this really is where preparation can optimise your tunnel time. Having manufactured all the test parts and practised fitting, it will be apparent that in many cases it's quicker removing parts than fitting them. So see if you can design at least some of your schedule with parts already fitted. There may be reasons why this isn't appropriate (some tests parts might interact and it wouldn't be useful to run them conjointly), or you may simply want to start in a specific baseline trim. At the very least spend time rehearsing changes so that fitting time is minimised and also quantified to help with scheduling.

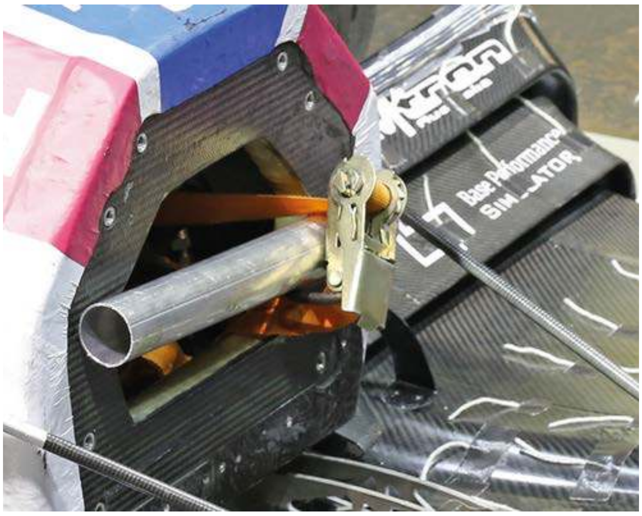
Allow some contingency, too; Murphy's Law *will* manifest itself at some point in the day. And if changes require jacking the car up, consult with your tunnel operator on the best way to do this to avoid damage to the tunnel load cells or floor, and allow for some additional time to re-check the car's alignment before proceeding.

Plan time for flow visualisation, too, using a smoke plume wand if available, wool tufts (which will have been affixed prior to arrival at the tunnel) and test fluid, if applicable. Time spent photographing and videoing this can be valuable for post-session review, but it also eats quickly into your allotted test period.

Your wind tunnel will request key dimensions in advance. Front and rear track plus tyre widths, and wheelbase, will enable the wind tunnel team to set up the load cells ready for your car to be rolled into place on arrival.

Photos: S. McBeath except where stated

Wooden wheel shims that fit within the load cell periphery can be used to adjust the ride height



A ratchet strap around a tube and the brake pedal clamps the brakes on firmly

Width and height enable an estimate of frontal area (see box out at the foot of this page), unless you are able to provide an accurate value for this; frontal area enables the measured forces to be output as coefficients. It's also useful to know what the front to rear static weight distribution of your car is, because this will often provide a rough target for downforce balance.

Other measurements that you can usefully make in advance for your own benefit include front and rear ride heights (at normal tyre pressures and with driver aboard) at easily accessed reference points that enable rapid verification in the tunnel. Another useful time saver is to work out what effect a turn on spring platforms or push/pullrods has on ride height so that pre-determined incremental changes can be quickly made without needing checking.

Or, if ride height is not going to be quickly adjustable this way, an alternative method (if there will be no wheel rotation via a moving floor or rollers) is to start with the car at its lowest envisaged ride heights and prepare some tyre contact patch-sized shims made from, say, plywood in suitable thicknesses like 3mm, 5mm, 10mm and 20mm (as appropriate) to enable incremental ride height and rake adjustments. There is another possible approach with ride heights, perhaps more applicable to high downforce cars. Instead of setting the car up on its springs and dampers and accepting that there will be some compression due to downforce (which you may be able to log on the car during the session) you could use adjustable 'dummy shocks' in place of the spring/dampers. Ride heights and rake are adjusted with these, but being solid links they do not compress with downforce. The choice is yours.

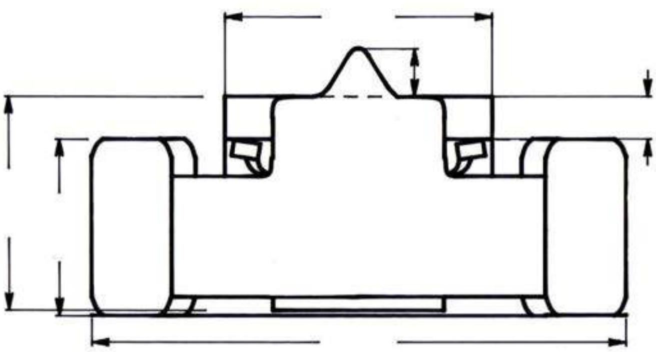
Once you know the total forces, and especially the front to rear split of vertical forces, you are in a much better position to design a programme

Dummy driver

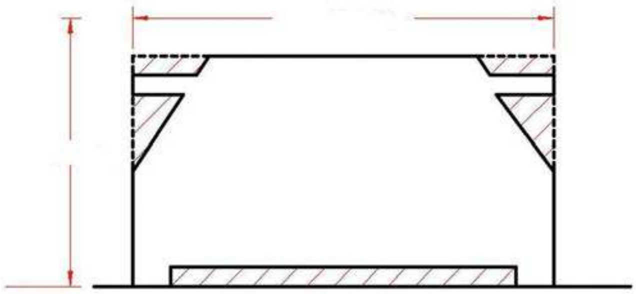
Other key details include checking that your wind tunnel can provide a crash-helmet-wearing dummy if your car is open topped. And, vitally important, make sure you have a means of clamping the brakes on firmly during testing to ensure the car doesn't move when the wind is turned on. Suitable methods include using a strap to pull the brake pedal towards the front bulkhead or a rod pressing between the pedal and the seat frame – the car will most likely be put in gear too as a back-up.

Another important preparation you need to see to is to organise the attendees. A structured team is required, with a designated leader and decision maker; a configuration notes maker/photograph taker (possibly the leader); and a well-organised small group (probably two to four people, as appropriate) to carry out configuration changes. The leader may well be the team's aerodynamicist, but whoever takes on the task has the primary responsibility of ensuring that the session is organised slickly and efficiently; data analysis should not, generally, hold up the wind tunnel session.

Estimating frontal area



Estimating frontal area on an open wheel car requires breaking the front silhouette down into discrete rectangular and triangular areas that are more easily calculated



You can estimate the frontal area of a closed racecar by subtracting the approximate area of the shaded portions in the diagram from the area given by the height x width

If your operation does not actually have an aerodynamicist available to advise before and during your session, your wind tunnel can probably provide one if pre-booked. Although this may incur an extra fee an experienced adviser can be a valuable asset, especially in the early stages of development.

At the tunnel

On arrival, the car will be set up on the wind tunnel balance. Tyres invariably need cleaning prior to this to avoid potential debris contamination of the load cells (or rollers if applicable), and tyre pressures and ride heights will be set and checked. The load cells will hopefully be in the correct locations derived from the track and wheelbase dimensions provided earlier, and the car will then be carefully aligned on the load cells parallel to the airflow, with the steering centred. If appropriate the test dummy will be installed in the racecar and, optionally, any ballast to simulate the driver's weight will be added, if this is needed to obtain the correct static ride heights.

Some full-scale wind tunnels with fixed floors have methods of dealing with the boundary layer ('stagnant' air that develops along the wind tunnel floor through viscous friction) and some do not. Even production-based racecars tend to run closer to the ground than their progenitors and bespoke racecars generally run closer still to the ground. So if boundary layer control is an available option, it's obviously best to utilise it. If it's not available then flows between the car's underside and the ground will be less representative of conditions out on track, and if the underbody is used for downforce generation then this component will be under-estimated. If wheel rotation is also available then this too should be utilised, although trip strips in the right location can better simulate rotating wheel separations on stationary wheels on open wheelers.

Clearly the preferred option is to have a moving ground belt available; some wind tunnels have a central belt between the wheels, while the sophisticated Windshear facility in the USA has a full width moving ground belt (boundary layer removal by suction ahead of the belt is still a pre-requisite). However, this is not to say that lack of a moving ground belt or boundary layer control or rotating wheels means you cannot get useful data from a wind tunnel; invaluable information on responses and trends is still obtainable.

The car being carefully aligned on the load cells; supplying the wind tunnel with its dimensions before the session is crucial

On open wheeler racecars trip strips can be used on stationary wheels to simulate their rotation more effectively

It's useful to know what the front to rear static weight distribution of your racecar is

The process

The car is now set up and you're ready to get that all-important baseline data. Everyone gathers expectantly around the control room PC displays as the wind is turned on and forces and coefficients start to be generated, logged and displayed. *Racecar Engineering*'s sessions at MIRA usually begin with a reasonably low air speed to ensure everything on and around the vehicle is secure. The speed is then increased to, say, 60mph for the first data sampling, and then usually to the maximum available of around 80mph (130km/h or 36m/s) for further sampling. This process ensures the car settles (or it indicates if something is insecure), and also allows a comparison between coefficients at different speeds; differences may be down to so-called Reynolds effects, where flow separation points, and hence coefficients, can alter with speed, or they could be down to downforce-induced ground clearance reduction at higher speed leading to yet greater downforce generation by ground-proximity devices.

These initial runs also indicate what level of repeatability is to be expected. Coefficients are generally reported to three decimal places, and duplicate readings from a single run should be within one per cent. For example, if the drag coefficient was 0.500, any variation between repeat results should be no greater than 0.005, or five counts. In practice, duplicates are generally within two or three counts. If variation consistently exceeds this level, stop to look for reasons – something on the car may be loose or perhaps a device is stalling, either of which can create unsteady flows.

Once underway, it's usually then a case of running through scheduled configuration changes, taking notes and photos, and logging results. The wind tunnel data acquisition system generates an electronic file or paper printout at session's end. But it helps the results to sink in at the time if the key data is tabulated on paper or in a spreadsheet. It also helps, where appropriate, to plot results mapped over a range of angles, heights or distances (again with pencil and graph paper or on a spreadsheet) at the time. Trends – and deviations from trends – are much easier to spot using graphs.

From this writer's experience some results will seem suspicious, counter-intuitive or just surprising. So, if time permits, it can be useful to pause and use flow visualisation with the smoke plume and maybe other media to examine the flow in areas of interest, hopefully to improve understanding. Time is usually tight, though, so be prepared to draw a decisive line under poor results and move on to the next configuration. Negative results still represent positive knowledge gains and are no less valuable.

It's always worth returning the car to its initial baseline configuration during a session, and possibly at the end too if practicalities and time permit, to ensure there has been no drift in results or, if there is a difference, to use the check as a new baseline by which to gauge subsequent runs. There shouldn't be much change but sometimes racecars do settle on their suspension, or parts don't go back on exactly as they originally fitted.

Data interpretation

On that first wind tunnel visit it can take a while to home in on the numbers that matter on the data acquisition PC screen. MIRA provides a printout of the results that appear on screen, and examples are shown in **Figures 1** and **2**.

There are two basic formats, displaying either forces or coefficients, and each has its adherents and uses. The load cells under the wheels measure absolute aerodynamic forces exerted horizontally, vertically and laterally at the tyre contacts. The coefficients are calculated using the basic aerodynamic force equations, which include the frontal area of the car; hence a reasonably accurate estimate of frontal area makes the coefficients meaningful.

The red boxes in **Figures 1** and **2** highlight the columns that are of most value, but let's quickly run through each printout to see why. Looking at the force printout in **Figure 1** (from a Lotus Exige seen in Aerobytes V17N8 to 10), from left to right, the run/configuration number,

Aerodynamic coefficients

Your results will appear as a set of numbers on a spreadsheet or a printout (see Figures 1 and 2 on the right). The abbreviations used are explained in this glossary

CD (or CX):	drag coefficient
CY:	side force coefficient
CL (or CZ):	lift coefficient (negative for downforce)
CMX:	aerodynamic roll moment coefficient
CMY:	aerodynamic pitch moment coefficient
CMZ:	aerodynamic yaw moment coefficient
CYF:	side force coefficient at front axle
CYR:	side force coefficient at rear axle
CLF:	lift coefficient at front axle (negative for downforce)
CLR:	lift coefficient at rear axle (negative for downforce)
XCP:	centre of pressure location along x-axis as percentage of wheelbase

The sophisticated Windshear tunnel in North Carolina has a full width moving ground belt – this is the 2014 spec TRD/TMG EVP002 Pikes Peak electric Radical (*Courtesy TRD*). Other wind tunnels will have a central belt between the car's wheels

MIRA Full-Scale Wind tunnel
Aerodynamic Forces and Moments

```
VEHICLE MAKE          LOTUS                         OVERALL LENGTH     3785 mm  (12.42 ft)
        MODEL        RACE CAR                       OVERALL WIDTH      1719 mm  ( 5.64 ft)
        TYPE                                        OVERALL HEIGHT     1163 mm  ( 3.82 ft)
        CONFIGURATION 9                             WHEELBASE          2300 mm  ( 7.55 ft)
        TRIM HEIGHT                                 TRACK   FRONT      1510 mm  ( 4.95 ft)
           FRONT     0.0                            TRACK   REAR       1570 mm  ( 5.15 ft)
           REAR      0.0                            FRONTAL AREA       1.74 Sq.m  (18.73 Sq.ft)
                                                    GROUND BOARD HT.   0.0 mm
MEASURED VEHICLE WEIGHT  996.4 kg  (2196.7 Lb)      B. L. FENCE        INSTALLED
FRONT AXLE LOAD:  405.7 kg  ( 894.4 Lb),   REAR AXLE LOAD:  590.7 kg  (1302.3 Lb),
MEASURED CENTRE OF GRAVITY   214 mm  (  0.70 ft) Behind  Reference Centre
No Moment Ref. offsets.    Vehicle Position Offsets:  X-  25.0 mm,  Y-   0.0 mm.
```

ALL SCALED TO A WINDSPEED OF: 67.10 m/s (150.10 mph, 241.56 kph)

RUN/CONF NO.		WIND SPEED	YAW ANGLE	FORCES Newtons			MOMENTS Newton.m			AXLE LOADS				DRAG POWER	Lift/ Drag	FRONTAL AREA
		m/s	Deq	DRAG	SIDE-F	LIFT	MX	MY	MZ	YF	YR	LF	LR	kW	L:D	Sq.m
1/	1	27.50	0.0	2691.1	-39.3	-3031.8	-27.0	1323.9	-36.3	-35.4	-3.9	-940.3	-2091.5	179.1	-1.127	1.740
2/	1	27.50	0.0	2687.1	-34.0	-3026.5	-22.6	1335.1	-39.5	-34.2	0.2	-932.8	-2093.7	178.9	-1.126	1.740
3/	2	27.52	0.0	2625.0	-27.2	-2903.7	-9.3	1085.7	-52.0	-36.2	9.0	-979.8	-1923.9	174.7	-1.106	1.740
4/	2	27.51	0.0	2637.3	-25.4	-2912.1	2.7	1096.6	-49.8	-34.3	8.9	-979.3	-1932.9	175.5	-1.104	1.740
5/	3	27.42	0.0	2793.6	-42.2	-3164.4	-27.2	1603.1	-23.5	-31.3	-10.9	-885.2	-2279.2	186.0	-1.133	1.740
6/	3	27.43	0.0	2785.7	-44.8	-3158.1	-35.4	1602.8	-24.6	-33.1	-11.7	-882.2	-2275.9	185.5	-1.134	1.740
7/	4	27.50	0.0	2644.2	-27.3	-2947.2	-2.7	1248.6	-51.8	-36.2	8.9	-930.8	-2016.5	176.0	-1.115	1.740
8/	4	27.50	0.0	2647.1	-33.8	-2944.8	-9.2	1250.0	-49.2	-38.3	4.5	-928.9	-2015.9	176.2	-1.112	1.740
9/	5	27.51	0.0	2541.3	-44.3	-2519.6	-18.0	386.4	-24.2	-32.7	-11.6	-1091.8	-1427.8	169.1	-0.991	1.740
10/	5	27.50	0.0	2551.4	-48.3	-2530.0	-24.9	390.1	-22.9	-34.1	-14.2	-1095.4	-1434.7	169.8	-0.992	1.740
11/	6	27.48	0.0	2715.5	-40.6	-2874.7	-18.0	1023.6	-32.3	-34.3	-6.3	-992.3	-1882.4	180.8	-1.059	1.740
12/	6	27.46	0.0	2720.0	-43.0	-2881.2	-16.5	1019.8	-29.3	-34.2	-8.8	-997.2	-1884.0	181.1	-1.059	1.740
13/	7	27.44	0.0	2705.8	-34.4	-2828.9	-2.4	985.1	-26.9	-28.9	-5.5	-986.2	-1842.8	180.1	-1.046	1.740
14/	7	27.45	0.0	2699.1	-36.2	-2824.6	-19.5	986.0	-28.9	-30.7	-5.5	-983.6	-1841.0	179.7	-1.046	1.740
15/	8	27.38	0.0	2695.0	-54.8	-2839.2	-31.5	1042.5	-11.1	-32.2	-22.6	-966.3	-1872.9	179.4	-1.053	1.740
16/	8	27.44	0.0	2675.6	-51.4	-2814.0	-38.2	1029.9	-19.0	-33.9	-17.5	-959.2	-1854.8	178.1	-1.052	1.740
17/	9	27.38	0.0	2377.0	-68.6	-3334.2	-119.9	1448.5	56.7	-9.7	-58.9	-1037.3	-2296.9	158.1	-1.403	1.740
18/	9	27.32	0.0	2419.6	-64.5	-3350.9	-120.2	1458.0	51.1	-10.0	-54.4	-1041.5	-2309.4	160.9	-1.385	1.740

Figure 1: MIRA printout showing forces and moments for a Lotus Exige. Red boxes highlight columns that are of most value

MIRA Full-Scale Wind tunnel
Aerodynamic Coefficients

```
VEHICLE MAKE          LOTUS                         OVERALL LENGTH     3785 mm  (12.42 ft)
        MODEL        RACE CAR                       OVERALL WIDTH      1719 mm  ( 5.64 ft)
        TYPE                                        OVERALL HEIGHT     1163 mm  ( 3.82 ft)
        CONFIGURATION 9                             WHEELBASE          2300 mm  ( 7.55 ft)
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           FRONT     0.0                            TRACK   REAR       1570 mm  ( 5.15 ft)
           REAR      0.0                            FRONTAL AREA       1.74 Sq.m  (18.73 Sq.ft)
                                                    GROUND BOARD HT.   0.0 mm
MEASURED VEHICLE WEIGHT  996.4 kg  (2196.7 Lb)      B. L. FENCE        INSTALLED
FRONT AXLE LOAD:  405.7 kg  ( 894.4 Lb),   REAR AXLE LOAD:  590.7 kg  (1302.3 Lb),
MEASURED CENTRE OF GRAVITY   214 mm  (  0.70 ft) Behind  Reference Centre
CD has been reduced by  0.004 due to HBL factor of   0.700
No Moment Ref. offsets.    Vehicle Position Offsets:  X-  25.0 mm,  Y-   0.0 mm.
```

RUN/CONF NO.		WIND SPEED	YAW ANGLE	FORCE COEFFICIENTS			MOMENT COEFFICIENTS			AXLE LOAD COEFFICIENTS				CENTRE OF PRESSURE	Lift% Front	FRONTAL AREA
		m/s	Deg	CD(-CX)	CY	CL(-CZ)	CMX	CMY	CMZ	CYF	CYR	CLF	CLR	XCP	%	Sq.m
1/	1	27.50	0.0	0.556	-0.008	-0.632	-0.002	0.120	-0.003	-0.007	-0.001	-0.196	-0.436	0.0	31.0	1.740
2/	1	27.50	0.0	0.555	-0.007	-0.630	-0.002	0.121	-0.004	-0.007	0.000	-0.194	-0.436	0.0	30.8	1.740
3/	2	27.52	0.0	0.543	-0.006	-0.605	-0.001	0.098	-0.005	-0.008	0.002	-0.204	-0.401	0.0	33.7	1.740
4/	2	27.51	0.0	0.545	-0.005	-0.607	0.000	0.099	-0.005	-0.007	0.002	-0.204	-0.403	0.0	33.6	1.740
5/	3	27.42	0.0	0.578	-0.009	-0.659	-0.002	0.145	-0.002	-0.007	-0.002	-0.184	-0.475	0.0	28.0	1.740
6/	3	27.43	0.0	0.576	-0.009	-0.658	-0.003	0.145	-0.002	-0.007	-0.002	-0.184	-0.474	0.0	27.9	1.740
7/	4	27.50	0.0	0.547	-0.006	-0.614	0.000	0.113	-0.005	-0.008	0.002	-0.194	-0.420	0.0	31.6	1.740
8/	4	27.50	0.0	0.547	-0.007	-0.613	-0.001	0.113	-0.004	-0.008	0.001	-0.193	-0.420	0.0	31.5	1.740
9/	5	27.51	0.0	0.525	-0.009	-0.525	-0.002	0.035	-0.002	-0.007	-0.002	-0.227	-0.297	0.0	43.3	1.740
10/	5	27.50	0.0	0.527	-0.010	-0.527	-0.002	0.035	-0.002	-0.007	-0.003	-0.228	-0.299	0.0	43.3	1.740
11/	6	27.48	0.0	0.561	-0.008	-0.599	-0.002	0.093	-0.003	-0.007	-0.001	-0.207	-0.392	0.0	34.5	1.740
12/	6	27.46	0.0	0.562	-0.009	-0.600	-0.001	0.092	-0.003	-0.007	-0.002	-0.208	-0.392	0.0	34.6	1.740
13/	7	27.44	0.0	0.559	-0.007	-0.589	0.000	0.089	-0.002	-0.006	-0.001	-0.205	-0.384	0.0	34.9	1.740
14/	7	27.45	0.0	0.558	-0.008	-0.588	-0.002	0.089	-0.003	-0.006	-0.001	-0.205	-0.383	0.0	34.8	1.740
15/	8	27.38	0.0	0.557	-0.011	-0.591	-0.003	0.094	-0.001	-0.007	-0.005	-0.201	-0.390	0.0	34.0	1.740
16/	8	27.44	0.0	0.553	-0.011	-0.586	-0.003	0.093	-0.002	-0.007	-0.004	-0.200	-0.386	0.0	34.1	1.740
17/	9	27.38	0.0	0.491	-0.014	-0.695	-0.011	0.131	0.005	-0.002	-0.012	-0.216	-0.478	0.0	31.1	1.740
18/	9.	27.32	0.0	0.500	-0.013	-0.698	-0.011	0.132	0.005	-0.002	-0.011	-0.217	-0.481	0.0	31.1	1.740

Figure 2: This shows the Exige data as coefficients; which makes it easier to quickly spot trends and quantify gains or losses








Negative results still represent positive knowledge gains and are no less valuable

wind speed and yaw angle are self-explanatory. The next three columns are the basic total forces; drag, side force and lift (negative when it's downforce). Here the major forces are drag and downforce, with small side force being logged. Side force arises either from a yaw angle or from vehicle asymmetry. In this case side force is very small compared to the drag and downforce, and can be ignored.

The moments *MX*, *MY* and *MZ* arise from the distribution of the aerodynamic forces around the centre of gravity. Here there's a pitching moment (about the *y*-axis) arising from more downforce at the rear, but the *LF* and *LR* values tell us this in more useful terms.

The axles loads *YF* and *YR* are the side forces measured at each axle, and are negligibly small here. The vertical loads *LF* and *LR* are important though, showing the split of downforce on the front and rear wheels ($LF + LR$ = total lift). Drag can be more usefully expressed as horsepower absorbed, and the next column shows this in kilowatts (divide by 0.746 to convert to BHP). And aerodynamic efficiency is frequently expressed as lift divided by drag (L/D).

Although coefficients (**Figure 2**) are just a mathematical treatment of forces, they can make it easier to quickly spot trends and quantify gains or losses. Note that as with the forces, $CYF + CYR = CY$, total side force, and $CLF + CLR = CL$, total lift.

This printout format also offers to calculate the Centre of Pressure, *XCP*, which is the point at which the total of the aerodynamic forces is effectively exerted. But the Lift%Front is perhaps a more useful way of expressing the aerodynamic balance that is calculated, as $[CLF / (CLF + CLR)] \times 100$.

Of all these figures, the ones to concentrate on in most cases will be lift and drag, whether as forces or coefficients, L/D and balance as Lift%Front, as highlighted by the red boxes. Balance is key in just about every case, whereas the trade-off between downforce (if it's allowed to be generated in the category you compete in) and drag (which is generated by every racecar) is very much down to your own particular racecar and its competition environment.

Once you have started generating data from the wind tunnel, the next questions will centre on what aerodynamic configurations you plan to test in your next session.

But here is another truism to end on: you will certainly learn a huge amount during your wind tunnel session, but you will also leave with more questions than answers.

Wind tunnel testing Dos and Don'ts

Do

- Plan and prepare well
- Forward the car's track and wheelbase dimensions to the wind tunnel in advance of the session
- Pre-fit parts where possible
- Have a means of clamping the brakes on
- Ensure all temporary parts are securely affixed
- Predetermine exact effects of ride height adjustments
- Have packs of tyre shims to alter ride height if required
- Be methodical; work through your schedule a step at a time
- Have one person to take notes and photos
- Have one person to make decisions
- Have a small group to make changes
- Always have materials and tools ready for the next configuration change
- Test a baseline set-up periodically
- Allow time for flow visualisation
- Run repeats on key or suspect tests
- Investigate the cause of poor duplicate results
- Use the best floor boundary layer control available
- Analyse data fully after the session
- Be prepared to test at the track to validate conclusions

Don't

- Turn up without a plan
- Squander valuable tunnel time in discussion or decision making
- Change more than one thing at a time
- Place absolute faith in the results from parts near the ground in a fixed floor tunnel, especially if there's no boundary layer removal. Trends can still be useful if treated with caution, however

Commercially available full-scale wind tunnels

This is by no means a complete list but the wind tunnels here are big enough and/or sophisticated enough to accept a full size racecar and yield useful data

Name (Country)	Test section area, m²	Maximum speed	Comments	Web address
Aerodyn (USA)	17.0	209km/h	Closed jet, contoured wall (option for slotted wall), boundary layer suction, rotating wheels. Optimised for stock cars, for example, NASCAR	www.aerodynwindtunnel.com
A2 (USA)	adaptable	137km/h	Closed jet, contoured walls, adaptable ceiling, passive boundary layer removal	www.a2wt.com
Darko (USA)	7.7	~130km/h	Closed jet, contoured walls, fixed floor	www.darkotech.com
DNW LLF (Germany/ Netherlands)	90.25 max, configurable	547km/h (depending on configuration)	Closed or open jet configurations, various boundary layer controls including moving ground, tripping, blowing	www.dnw.aero
Lockheed Martin (USA)	33.6	321km/h	Closed jet, fixed floor with tangential blowing boundary layer control	www.lockheedmartin.com
MIRA FSWT (UK)	35.0	133km/h	Closed jet, fixed ground, boundary layer trip fence	www.mira.co.uk
Monash (Australia)	10.4 at nozzle	180km/h	Open jet, fixed floor	www.monash.edu/engineering/our-research/facilities/wind-tunnel-facility
NRC (Canada)	82.8 ('9 metre wind tunnel')	198km/h	Closed jet, boundary layer removal by upstream suction, and lengthened ex-Pininfarina moving central ground belt plus wheel rollers	www.nrc-cnrc.gc.ca/eng/solutions/facilities/index.html
Pininfarina (Italy)	40.3	250km/h	¾ open jet, moving ground 'T-belt' comprising long central belt plus short belts under front wheels	www.pininfarina.com/en/services/wind_tunnel
SAA GIE S2A (France)	24.0 at nozzle	240km/h	¾ open jet, moving ground central belt plus driven wheels (max. speed 200km/h), boundary layer suction	www.soufflerie2a.com
Windshear (USA)	16.7 at nozzle	289km/h	¾ open jet, single belt moving ground.	www.windshearinc.com


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Calling the shots

Outside of war zones there are few spheres as reliant on effective strategy and tactics as motorsport – but just how do you make quick and correct decisions in the white heat of a racing battle?

By RICARDO DIVILA

When there is any war, it does help to have a plan. Motor racing is war in a civilized fashion, thus it will also need to have some planning. The whole process will involve tactics and strategy, two terms that are often conflated. Tactics are the actual means used to reach an objective, while strategy is the overall campaign plan, which involves complex operational patterns, activity, and decision-making that will govern the tactical execution. Tactics also tend to be shorter-term and more specific than strategies.

The car design brief is an example of strategy. It analyses what your objectives are, how you are going to achieve it and how you are going to use your resources, fit the rules, all the while factoring your opponents' capabilities.

Operating a strategy at a race takes in the track format, weather, where you end up on the grid (which will be part of tactics, by choosing your amount of fuel you use for qualifying, for example, in the cases where you must start with the fuel you have after qualifying) and driver performance (when running multiple drivers in the same car they will probably have different lap times and fuel consumption).

Simulation is a useful strategic tool. It is commonly used in vehicle dynamics to see what a parameter change will do to lap times. For example, changing settings and seeing the gains or losses, refining the car's performance. For racing, the other simulations that are very useful are those that will consider race tactics depending on what you and the opposition can do; say if you have pit stops, calculating the window in which it will operate and, if it is wide enough due to fuel tank capacity, which lap will be the optimum one to pit on.

In endurance racing it will also take into account the various yellow flags that may appear, full course yellows and safety cars, and it

Having considered all the possible variations also helps you to be better able to make quick decisions when they are needed

In F1 the timing of the pit stop can make the difference between winning and finishing off the podium. It's little wonder then that much of a team's strategy is focussed on the stops will tell you which is the best moment to come in to the pits with a minimum time loss.

Having considered all the possible variations also schools you into being able to make better quick decisions when they are needed, as the time differences between different alternatives ends up being very small per lap. Running alternate scenarios often gives you a firmer grasp of the subject. Nothing beats numbers.

Part of the programming will, of course, be checking the rules. A series that has wave-through behind the safety car to bring everybody on to the lead lap will have different algorithms to a FCY (full course yellow), for example. Even the race director will influence your strategy. Some throw safety cars in with gay abandon. Others just use local yellow flags. Studying previous years' data will also mean checking which race director was supervising at the time. This is a lot of research to do in the winter season. But diligence pays off.

Here's how it all works in practice. You can calculate time from a given track position to the pits, and in the case of a safety car and you are ahead, a lap data printout over time will give the car position on track at all points (**Figure 1**).

If you do not have real-time telemetry it will also predict how much fuel you have on board and determine the number of laps you can run behind the safety car before you have to pit.

In these cases it is common to have the anxious discussions with the driver by radio to estimate how long the SC or FCY will last, while looking up your tactic matrix depending on what lap you are on, how long to the end of the race and your position; apart from the driver routinely being questioned every five laps as to the amount of fuel being used. Being able to

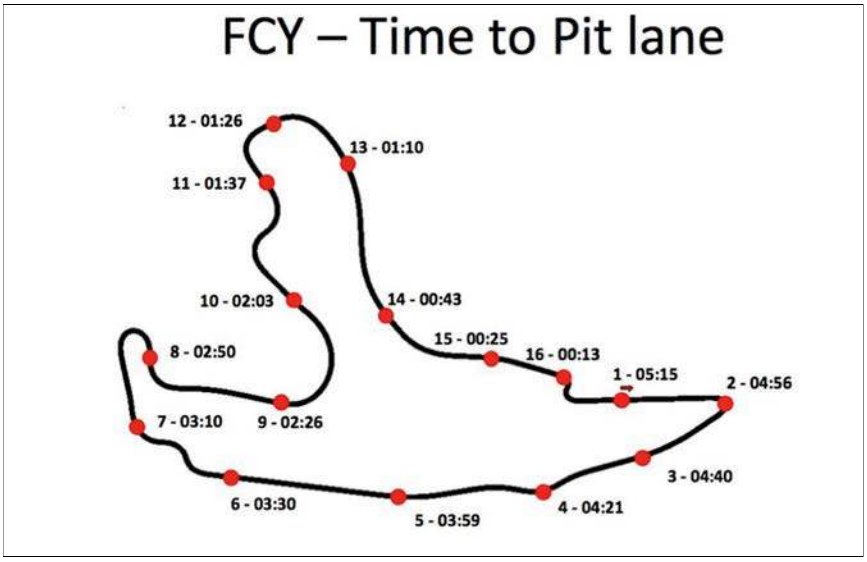

Figure 1: Time from a given track position to the pit lane at Spa. This easy to read diagram can be very useful

Track Info			
Length (km)	13.626	1st Stint (laps)	11
Ref. Lap Time	03:46.	Normal Stint (pit lap)	12
Ref. Lap Time - Q	03:39.	Stint Duration (min.)	45:12
Pit In/Out Loss	00:38.	Expected Stints	32
Ref. Fuel Cons. (Lt/Lap)	6.10	Race Expected Laps	384
Tank Capacity (l)	74.3	Fuel Rate (l/s)	2.63
		Fuel Density (kg/l)	0.73

Session	Start	End	Day
AM	09:00	13:00	Sun
PM	14:00	18:00	Sun

DRIVING TIME				
Drivers	MR	JC	KG	TOTAL
Laps	60	22	32	114
Kms	817.6	299.8	436.0	1553.4

Total Fuel Used
695.4 liters

TYRES									
Set	1	2	3	4	5			101	201
Compound	B	B	B	C	C			INTER	WET
Start Km	0	0	0	0	0			0	0
Laps Event	18	26	22	36	12	0	0	0	0
End Km	245.3	354.3	299.8	490.5	163.5	0.0	0.0	0.0	0.0

AM 04:00

Run	Driver	Tyre Set	Laps	Start	End	Work	Tyre Change	Driver Change	Refuel	Fuel Start	Fuel End	Refuel (l)	Refuel (kg)	Refuel (s)	Comments
1	JC	1	1	09:00	09:04	00:05	NO	NO	NO	56.0	49.9				Check
2	JC	1	3	09:09	09:21	00:05	NO	NO	YES	49.9	31.6	18.4	13.4	7.0	Tyre P/Balance assessment
3	JC	1	3	09:26	09:38	00:05	NO	NO	YES	50.0	31.7	18.3	13.4	7.0	Tyre P/Balance assessment
4	JC	1	3	09:43	09:55	00:02	NO	YES	YES	50.0	31.7	18.3	13.4	7.0	Engine Map 1
5	KG	1	3	09:57	10:09	00:02	NO	NO	YES	50.0	31.7	42.6	31.1	16.2	Change Practice/Check Balance
6	KG	1	5	10:11	10:30	00:02	YES	YES	NO	74.3	43.8				Check Balance/Engine Map 1
6	MR	2	2	10:32	10:40	00:05	NO	NO	YES	43.8	31.6	42.7	31.2	16.2	Pit Practice/Check Car+Track
7	MR	2	12	10:45	11:31	00:02	NO	NO	YES	74.3	1.1	73.2	53.4	27.8	Long run
8	MR	2	12	11:33	12:19	00:02	YES	NO	YES	74.3	1.1	73.2	53.4	27.8	Long run
9	MR	3	10	12:21	12:59		NO	NO	NO	74.3	13.3				Pit Practice/Long run
7							NO	NO	NO						

Drivers	MR	JC	KG	TOTAL	Comments:
Laps	36	10	8	54	Check Tyre/Plank/Brake Wear. Debrief and adjust balance as needed
Kms	490.5	136.3	109.0	735.8	

FCY – time to pit lane

PM 04:00

Run	Driver	Tyre Set	Laps	Start	End	Work	Tyre Change	Driver Change	Refuel	Fuel Start	Fuel End	Refuel (l)	Refuel (kg)	Refuel (s)	Comments
1	KG	3	12	14:00	14:45	00:02	YES	NO	YES	74.3	1.1	73.2	53.4	27.8	Long run
2	KG	4	12	14:47	15:33	00:02	NO	YES	YES	74.3	1.1	73.2	53.4	27.8	Long run
3	MR	4	12	15:35	16:21	00:02	NO	NO	YES	74.3	1.1	73.2	53.4	27.8	Pit Practice/Long run
4	MR	4	12	16:23	17:09	00:02	YES	YES	YES	74.3	1.1	73.2	53.4	27.8	Assess triple stint
5	JC	5	12	17:11	17:57	00:02	NO	NO	NO	74.3	1.1				Pit Pratice/Long run
6							NO	NO	NO						
7							NO	NO	NO						
8							NO	NO	NO						
7							NO	NO	NO						

Drivers	MR	JC	KG	TOTAL	End of Session Comments:
Laps	24	12	24	60	Check Tyre/Plank/Brake Wear.
Kms	327.0	163.5	327.0	817.6	

Other Comments

Priority for the test should be to give as much driving time as possible to the drivers - MR's first Le Mans run and first Le Mans run for KG on a LMP2

We should get tyre pressures and also assess the durability of the tyres - we have to try a triple stint if we feel confident with the results from the morning.

Figure 2: Simple run sheets give you all the information you need to prepare for a track session. After the first session they can be amended and updated for the following session

stretch out your pit stops and possibly have one fewer, could enable you to jump another car.

Some strategies can leave you out on a limb. At Spa for a WEC race we had refined our fuel consumption so well that we knew that if we didn't have a fuel cough before Les Combes (which is point 6 on the **Figure 1** map) we could do an extra lap and come in to fuel with 0.3 litres in the tank. But we got caught out when there was a red flag on our in lap, and we had to sit on the grid waiting for the restart knowing there wasn't enough fuel in the tank for a full lap. No need for a manicure that day, nails were bitten down to the quick for the full lap, the driver cutting the engine on the downhill bits, running only in sixth gear; but he made it.

Combat readiness

But the important thing is, simulation will give you a structure as to what you are doing at the track. This will involve solving logistical problems that are inherent to operating cars under the series rules. These will include the mundane matters set by the team manager or transport manager regarding hotel bookings, ferry and plane tickets, all items the engineer wouldn't be involved in normally, but will also include booking the fuel, tyres and test items or race parts that will go into the mix, definitely in the engineering domain.

Outside single-driver formulae you can also be involved in deciding how many laps each driver will do in practice and race, contingent on their known pace, their need to learn the track and even on the sponsorship they bring.

So let's now look at different varieties of strategy and tactics there are. The specific racing classes will have very different requirements – from club racing right up to Formula 1 – all of which will be tied to the size and organisation of the team, length of race and the logistics involved. You must establish how you deploy your assets in the best way.

The run plan

The simple example will look at the predicted lap time, fuel consumption, session length and set-up changes programmed. Often called 'run plan' it is done at the workshop and gives you your fuel and tyre requirements – if not limited by the rules – so the team manager can budget, order the items and avoid the embarrassment of having the excess fuel being poured down some unsuspecting drain in the paddock (as the rental cars have all been refuelled and the truckie is averse to driving the transporter with a couple of 50 gallon drums of fuel in it, something frowned upon by ferry operators and the authorities for good reason).

It also gives you a good reality check on how the session might be, helping to make the decision of how you will programme the race weekend. Just letting the car loose, and hoping you can achieve all that needs to be done, often shows a lack of time perception. You will do fewer laps than you think. At the same time it will help you control when your tyres will be mounted, and when they have to go into the blankets if you can use them.

The simple run sheet (**Figure 2**) gives all information required to prepare for a session. After the first session it can be amended and updated for the following session, and so on. Copies for the mechanics, tyre men, engineers and drivers will bring them all up to speed as to when items will be needed, how much fuel, what tyres, when the car is due in and how much time should be allotted for work. The same sheet can be updated dynamically at the track as external events change the timing.

There will be an alternative Plan B for different weather conditions – if wet, or intermediate – as you will have checked the weather forecast and have an idea of the probability. Wet session lap times can be estimated roughly by previous history, but you will update when arriving at the track.

One other reference source, if there are multiple races during the weekend, will be the lap times in other classes. This will give the track conditions and what the delta to your class is. If they go faster than the previous year's data or the sessions are faster/slower than previous ↳

One other reference source, if there are multiple races during the weekend, will be the lap times from the other classes

					2nd stop			Expected	
DRIVER	CHANGE	CHANGE	CHANGE	STAY	CHANGE	Display=	5	15	Theo lts/lap
FUEL	OK	2 Stop	2 Stop	2 Stop	OK	Lap=	1	1.000	2.99
TIRE=	735	735	735	735	735	can go=	32	Tyre	Fuel left
	Base	Alt 1	Alt2	Real	Next	TO GO=	53	735	89.61
Total race=	54	54	54	54	54	2nd Stint	21		
Predicted fuel & tyre stop=	27	21	20	1	29	Fuel req	62		
Fuel start	98	60	98	97	60	Secs=	[illegible]		
Fuel total	165.86	165.86	165.86	165.86	165.86				
Fuel used	85.13	67.19	64.2	7.39	91.11				
Fuel 2 stop		38.67	3.66	61.47	14.75				
Fuel required 2nd stint	80.73	98.67	101.66	158.47	74.75				
Fuel required 3nd stint								Tot	91.61
DISPLAY MAX START=	490	300	490	485	300	3rd Stint	458	Fuel in	2
DISPLAY MAX SECOND=	403.65	493.35	508.3	792.35	373.75	Display=	0		Theo lts/lap
Fuel in tank	12.87	-7.19	33.8	89.61	-31.11	Lap=	53		2.92
Refuel quant	67.86	105.86	67.86	68.86	105.86	can go=	31		
Laps to go=	27	33	34	53	25	TO GO=	1	0	
Refuel rate lts sec	2.82	2.82	2.82	2.82	2.82				
Refuel time sec	24.1	37.5	24.1	24.4	37.5				
Lts/lap=	2.99	2.99	2.99	2.99	2.99				

Figure 3: An example of a simple alternatives chart, with the fourth column the live info and the sixth previewing the next pit stop. The cells in yellow are the inputs that might change


CD34
THE BEST JUST GOT
BIGGER
RPM 7400
KPH 126
4
LAP
00:00.0
BEST
00:00.0
OILP
AIRT
COOL
BATT
GEMS
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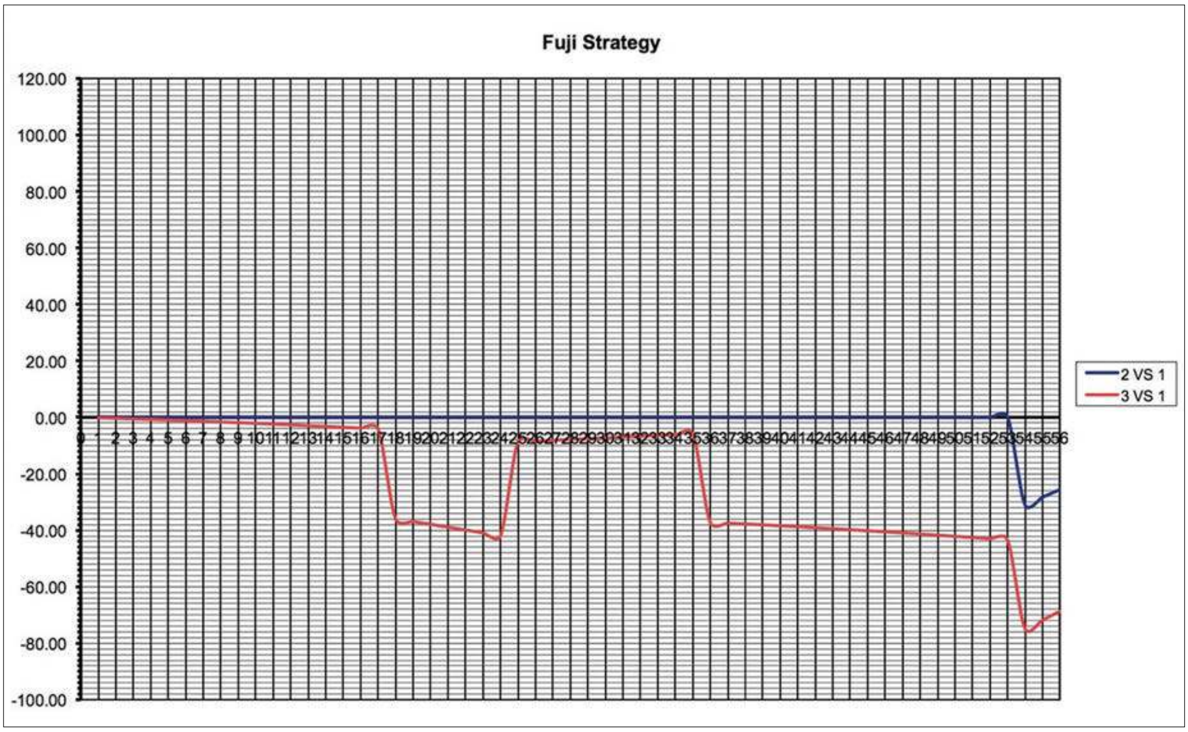

Figure 4: This shows a simple comparison of strategies for different runs, comparing a one-stop against a two- and three-stop. This chart actually dates from the 1980s

ones it will give you some idea of the track condition delta you can expect.

You would also run a more complex chart, taking into account every lap time, keeping tab on the time to go and fuel used, and if different to schedule – which is common – you will need to prioritise the tests you want to do while making sure all drivers get their run.

As a session starts, elapsed time is noted and reset on the schedule giving all data relevant, such as fuel left, time left, tyre mileage and tyre set number. At the end of the session you have a complete record of all data for that outing. Times can be corrected after, or even during, a run to maintain a running check on use of time – if variations occur this will enable you to re-schedule on the fly.

Tactical advances

Then there is the simulation for the race, trying out different tactics. This is usually done after free practice and qualifying, with relevant data from the practice sessions – by this time you will have a very good database of fuel used by different drivers and their consumption related to lap time and tyre degradation.

All of this information, plus your opponents' performance, is then run several times with different scenarios, and can be followed live with alternative pit stop, tyre choice and driver change options. Different columns will highlight the options and determine lap-by-lap what is the course to take, quantifying exactly where the fuel, tyre and driver options will influence track position and race laps over the time – if a time constrained race – or laps possible, proposing the pre-programmed options and the changes lap-by-lap

Figure 3 shows an example of simple choices with the postulated base and alternatives, with the fourth column live updated to race, and the sixth column previewing the next stop, or third. Cells in yellow are the inputs that can be altered during the event if there is changed fuel consumption.

Figure 4 shows a comparison of strategies for different runs, comparing a one-stop against a two- and three-stop. It's very simple (from the '80s) but it shows the sort of inputs and outputs of the time. It caters for tyre degradation and fuel weight, plus the length of the pit stop.

The basic simulation of race performance takes into account the effect of fuel weight, tyre degradation and track improvement. Finer detail also looks at weather conditions; rain, wind, the warming of the track, pit entry and exit condition, pit length and pit speed limits.

Other parameters are traffic expected, the probable performance of other cars and drivers and a matrix to choose who to fight and who to ignore. For example, do you really need to battle it out with a car that is not a championship contender, with all the risks this entails?

	most common result	avg deviation	points to drop	median	avg	avg per finish	DNFs or out of points	Estimated champ points median	Estimated champ points average	Target/ Achieved Conversion rate
Aiello	0	5.76	0	11	9.6818	11.833	4	242	252	0.92957746
Leslie D	0	4.36	2	9	8.6818	10.053	3	198	226	0.89528796
Thompson J	6	3.68	0	6	6.8571	9	5	132	178	0.66666667
Rydell R	0	4.7	0	5.5	6.3636	8.75	6	121	165	0.62857143
Plato J	0	4.7	1	5	5.85	6.8824	3	110	152	0.72649573
Neal M	0	5	0	4	4.6667	5.7647	4	88	121	0.69387755
Kox P	2	1.92	4	4	5	5.5556	2	88	130	0.72
MullerY	0	4.44	0	4	4.75	5.9375	4	88	124	0.67368421
Radermac	0	3.8	0	6	4.9474	6.2667	4	132	129	0.95744681
Boullion	5	1.8	3	5	4.5263	5.0588	2	110	118	0.98837209
Menu A	0	3.72	0	2	4.1111	6.7273	7	44	107	0.2972973
Reid A	0	3.12	0	3	3.4	5.6667	6	66	88	0.52941176
Cleland J	3	1.7	3	2.5	2.7143	3.1667	2	55	71	0.78947368
Brookes	0	0.6	0	0	0.4167	1.25	8	0	11	0
Blair	0	0.7	0	0	0.4167	1.6667	9	0	11	0
Spence	0	0.54	0	0	0.25	3	11	0	7	0
Cook	0	0.18	0	0	0.0833	1	11	0	2	0
Gallie	0	0	0	0	0	#DIV/0!	12	0	0	
Howell	0	0	0	0	0	#DIV/0!	12	0	0	
0	0	0	0	0	0	#DIV/0!	12	0	0	

Figure 5: This is one part of a season-long strategy in the BTCC. The team concerned kept a close eye on all of its rivals

Big data

Figure 5 is part of a wider strategy once used in a Super Touring championship, being updated every race after analysing the results. The inputs had several parameters that were substantially subjective, giving weight to inputs derived from observed previous races, like driver form regarding starts, accident proneness or car strengths and weaknesses on different tracks. It used data from previous years and was updated after every race during the championship. It was part of the tools used to win several BTCC and Super Touring crowns and at the same time highlighted areas to develop on the car side.


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Figure 6: This data was for calculating the first lap loss at different race tracks depending on the car's grid position

2000 Data								
Grid Position	Oz	Brazil	Imola	Silverstone	Barcelona	Nurburgring	Monaco	Montreal
1	6.2	7.1	1.2	4.1	4.2		3.2	5.3
2	6.2	8.3	2.4	4.529	5.34	4.9	5.5	6.3
3	6.9	7.2	6.1	5.645	7.9	5.5	6	8.8
4	8.2	8.2	5.5	4.978	6.93	7	7	9.2
5	7	11.1	9.2	9.041	6.43	8.8	7.4	10
6	8.5	9.9	8	6.095	9.2		9.6	8
7	9.8	11.2	8.6	8.172	10.25	9.2	9.1	11.8
8	9	11.9	7.4	9.81	9.81	9.8	10.3	10.8
9	11.5	14.6	6.7	10.97	12.39	8.2	8.4	10.2
10	9.7	13.2	11.2	7.368	10.49	12.1	12	12.4
11	12.3	14.3	12.6	10.328	12.69	12.8	10.8	13.2
12	12.4	12	9.6	10.678	10.95	10.8		14
13	11.3	13.4	11.5	12.91	13.92		13	13.1
14	13.8	14.7	10.4	13.997	13.49	10.5		14.9
15	15.7	16.1	11.8	11.462		11.5	13.4	15.6
16	12.8	15.5	10	12.27	11.743	14.2		
17	19.7	17.1	14	14.39	14.16	15.1	15.1	15.3
18		16	13	11.87	13.09	13		17.2
19	15.2	17.6	14.4	13.368	15.74	15.6	14.1	16.6
20			15	13.71	15.2	14.6	15.8	18.1
21	13.1		13.7	14.93	16.2	15		16.9
22	17.6			15.26		15.8	16.6	18.4
m	0.54	0.56	0.55	0.51	0.52	0.5	0.58	0.57
c	5.53	6.99	3.5	4.4	5.4	5.2	4.6	6.2

Figure 7: This takes the above further and also gives the fuel effect on time per kg, the number of laps, fuel consumption per lap and other parameters

Race	1st Lap Delta	1st Lap Gain	Pitlane Delta	Fuel Effect	Laps	Fuel Usage	Overtake	Race Offset	pitlane 99
Autopolis	5	0.55	17	0.03	64	2.126	1	2	14.2
Motegi	5	0.55	17	0.03	62	2.55	2		
Barcelona	5.2	0.54	18	0.03	65	2.35	1.5	3.6	
Hockenheim	5	0.55	14	0.025	45	3.2	2		11
Hungaroring	5	0.55	17	0.025	77	1.95	0		16.6
Imola	6.8	0.62	13	0.03	62	2.6	1.25	1.8	
Indianapolis	5	0.55	23	0.02	73	2	1		??
Interlagos	7	0.55	18	0.025	71	2.1	2	0.6	
Magny-Cours	5	0.54	12.5	0.023	72	2.1	2		13.5
Monaco	4.6	0.58	16.4	0.02	78	1.8	2	2.3	
Montreal	6.2	0.57	16.1	0.02	69	2.3	2	1.4	14
Monza	5	0.55	18	0.025	53	2.85	2		13
Nurburg	5.2	0.5	19.5	0.031	67	2.27	1.5	4.8	
Sepang	5	0.55	20	0.03	56	2.85	2		15
Silverstone	5	0.55	19.5	0.03	60	2.6	2		
Spa	5.2	0.63	16	0.034	44	3.35	2		13
TI	5	0.55	15	0.032	82	1.98	2		14.5
					64.7058824	2.410352941	155.964014		

Historic data and analysis of your opponents shows scenarios that have already been played out in real life, bringing a bit of grounded sanity to the usual blue-sky simulation scenarios. Any differences to your simulation and reality can then be changed, identifying the differences and making the changes to your software to correct them. Also, recent history is important too. Analysing the race you have just completed does give you a check on what really happened – and it should be then compared to your simulation to see which factors you have mistakenly chosen or not analysed.

There are actually some good examples of performance being gained without car set-up changes but through looking at the race data. With one driver, when looking at race lap-times it brought up the fact that often these started slowing down as soon as the five-lap countdown was shown on the board. Showing the lap time graph to the driver made him realise that he was losing considerable time by relaxing, knowing he would have a rest soon.

Another example thrown up by comparing simulation with reality, particularly at Le Mans, was discovering that the most efficient way to manage safety cars was to pit the lap the safety car came back in, or if you had adequate warning the lap before, depending on your relative position. Having a tyre just out of the blanket at operating temperature, then changing wheels rapidly and hitting the lap time targets quickly, could gain track position faster than losing less ground while pitting during the SC but losing time as tyres were cold for nearly half a stint after release.

Privateers running even the softest tyre available during night stints had trouble warming them up if cold after sitting behind the SC for a couple of laps. Once again, a straightforward strategy simulation would leave you with the decision to pit under a SC, theoretically, but adding the temp values to your simulation with data gleaned from real life measurements would prove otherwise.

General studies

As always, getting the data needed for the strategy simulation is difficult and painstaking. Historic data helps. Data sets from most racing series can be found online for students wishing to develop their skills in writing software for this. This facet is covered by the strategist and US Air Force Colonel John Boyd, who conceived the OODA loop, a practical concept designed to be the foundation of rational thinking in confusing or chaotic situations.

OODA stands for Observe, Orient, Decide, and Act. Boyd cautioned against first-conclusion bias, explaining that we cannot keep making the same decision again and again. The implication of this is that we should test the decisions we make at this point in the loop, spotting their flaws and including any issues in future observation stages.

Although Boyd is regarded as a military strategist, he didn't confine himself to any particular discipline. His theories encompass ideas drawn from various fields, including mathematical logic, biology, psychology, thermodynamics, game theory, anthropology, and physics. He described his approach as: 'A scheme of pulling things apart – analysis – and putting them back together – synthesis – in new combinations to find how apparently unrelated ideas and actions can be related to one another.' The same applies to motor racing.

We can incorporate testing into our decision-making processes by keeping track of outcomes in decision journals. Boyd's notes indicate that he may have done just that during his time as a fighter pilot. Rather than guessing how our decisions led to certain outcomes, we can get a clear picture to aid us in future orientation stages. Over time, our decision journals will reveal what works and what doesn't work.

Updating your simulation with observed real data not only refines it and makes it more accurate, but it also opens up new territory to explore and understand.

We can incorporate testing into our decision-making processes by keeping track of outcomes in decision journals

For instance, the data in **Figure 6** calculates your first lap loss at different tracks depending on your grid position. **Figure 7** then factors that in, and also gives your time loss on first lap, the fuel effect on time per kg of fuel, number of laps, fuel consumption per lap, difficulty factor for overtaking, pit lane time, etc. (note that this is quite old data, just for an example).

Fuel loads

The other version of simulation allows you to compare different tactics given previously researched tyre degradation over long runs and the effect of the weight of the fuel carried. This was a big part of GT500 racing in Japan, where the fuel regulations would mean the racecar was capable of doing only one pit stop in the race, and this ended up being the paradigm. Two drivers would make for only one driver change so it was logical to have only the one stop, as tyres were supplied in qualifying compounds and race compounds.

In Formula 1 it used to be the norm not to make a pit stop for fuel, until Gordon Murray pulled the rabbit out of the hat in the early 1980s, when at Brabham, and disappeared into the distance. In those days it was just fuel, but it rapidly evolved into changing the tyres, too, until the fuel stops were then banned. But we still have tyre stops, as the tyres are designed to have a pretty much fixed amount of useful laps, variable according to compound.

Once again, we can see that each championship will evolve different strategies because of different rules and constraints. IRL, as IndyCar was once known, is run around fuel strategy. The probable number of FCY keeps the engineers full time on the keyboard recalculating the windows (**Figure 8**).

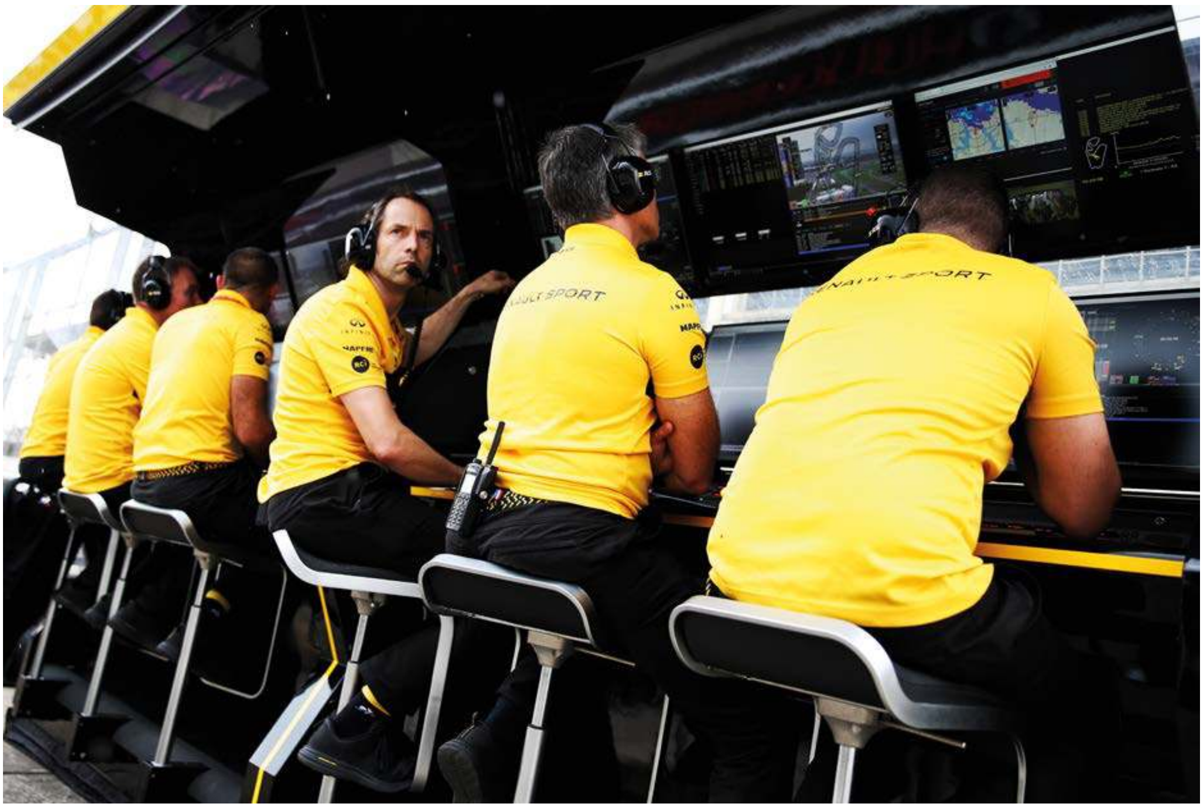
Being out of sync with the opposition due to yellow flags can make all the difference on the last laps. The fumbling through different fuel maps when running on vapour could get you to the flag first, or make you do that splash and dash which drops you way down the order.

Playing with the cost of weight, tyre degradation and pit stop times could nudge the tactic towards a two-stop strategy under certain conditions. Hot tracks, where tyre degradation would make the end of a stint much slower due to drop-off in the softer compound, could give you the option of still running the soft compound, starting with less fuel for shorter stints and gaining time by refuelling with less fuel, thus shorter, in the two stops. Additionally there is a gain coming in to an empty pit lane, out of sync with other cars, with the added possibility of then running outside the pack.

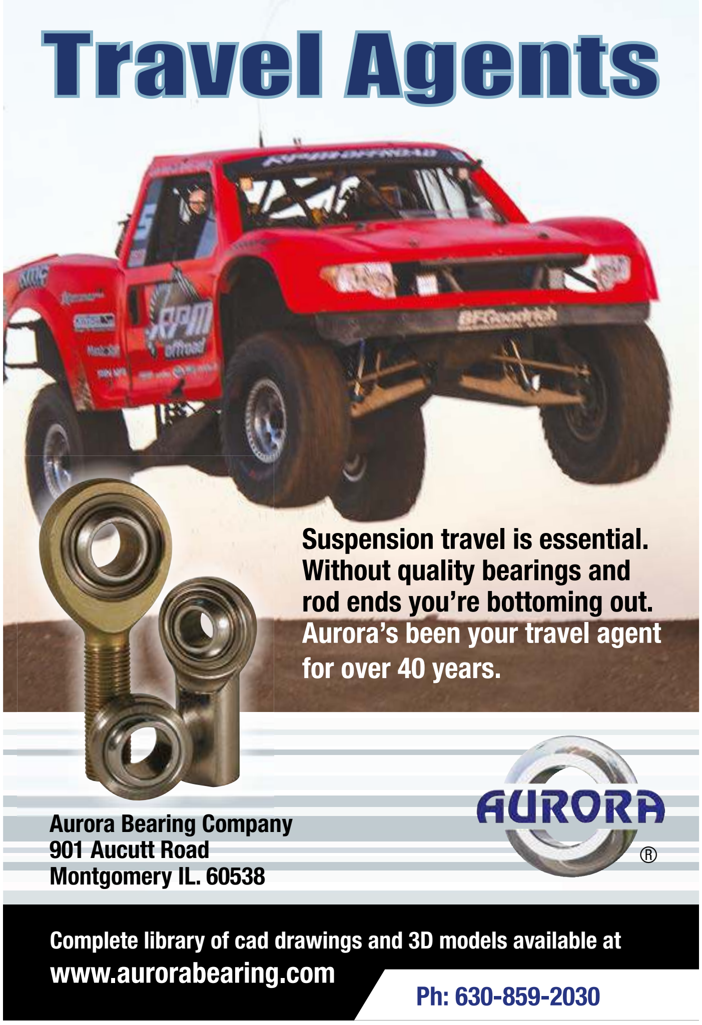
In one event preliminary simulation gave a mere eight second advantage for a two-stop,

Track			**Mex City**	0
Distance			2.774	1
Laps			72 / 65	2
LAPTIMES				3
Fast Lap (Qualify)			83.558	4
Fast lap (Race)			86.500	5
Std lap (Race)			87.500	6
Stop only time loss (yellow)				7
Pit lane time (tires)			30.900	8
Pit lane time (full fill)			34.900	9
ON TRACK			5.800	10
Stop loss TIRES			**25.100**	11
Stop loss FILL			**29.100**	12
Calc time loss				13
Calc time loss			30.000	14
Post pit time loss			11.000	15
				16
				17
Pit stop loss			**41.000**	18
Stop to Laptime RATIO				19
Pitstop % lap (tires)			**0.290**	20
Pitstop % lap (full fill)			**0.336**	21
PIT STOP ANALYSIS				22
50 --> 0 time			3.000	23
0 --> 50 time			3.500	24
Tire stop			7.500	25
Theo drive thru			19.900	26
Loss to Track				27
EST FUEL		2.06		28
Windows			**Tires**	29
Stop 1	19-22	Start	**Set 7 (4L)**	30
Stop 2	42-45	S1	**Set 9 (0L)**	31
Stop 3		S2	**Set 6 (1L)**	32
Add'l		S3	**Set 4 (4L)**	33
			Set 8 (4L)	34
OT TIME		60		35
				36
				37
				38
				39
TOTAL		**0.0**		40
GPL	*MPG*	2.4	DASH	41
1.26	*2.20*		91.7	42
1.28	*2.17*		90.3	43
1.30	*2.13*		88.9	44
1.32	*2.10*		87.6	45
1.34	*2.07*		86.3	46
1.36	*2.04*		85.0	47
1.38	*2.01*		83.8	48

Figure 8: A strategy data-check chart for an IRL oval race in the '90s



There has never been quite as much data to help make the right call in a race as there is now. In F1, engineers at the track (pictured) are also backed up by teams of strategists back at their base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but on arriving the track temperatures were higher than predicted and tyre deg was also higher, prompting us to move on to a three-stop strategy. This proved extremely effective; a fast first stint as the car was lighter, moving into the lead at the second stint, with the car getting to the top step on the last stint due to fresher tyres.

The alternatives had been pre-calculated, so when arriving at the race track and then checking the track temperatures and seeing the sunlight there, it then enabled us to work for a three-stop race from the first free practice.

When you have the advantage of surprise it destabilises the opposition, but sadly you can't do it every time. As Sun Tzu, the author of the classic text *The Art of War*, said: 'Let your plans be dark and impenetrable as night, and when you move, fall like a thunderbolt.'

Le Mans

The stipulated Le Mans fixed lap stint run in 2018 is an aberration, and negates any strategy and ploy you might be working towards. Let's hope it goes away. The energy amount given to the different classes are difficult enough as it is. Every time the rules on capacity changes you find that at best you can be just a couple of litres short of an extra lap. And with a 13.7km lap distance this means it is very dubious you can drag the car to the pits if you miss the right in-lap. **Figures 9** and **10** show a rather successful Le Mans pit stop strategy from an earlier time. The only drawback was we were gambling a bit, as coming through the backmarkers the one extra time could be a hazardous proposition.

As with anything you practice, if you do it right, the more you do it the better you will get. You'll start making better decisions more quickly. However, running strategy at the track in real-time can lead to wrong decisions through wrong simulation assumptions, so never lock yourself into a strategy that cannot be changed. And, always know where your car is.

One of the reasons I say this is because in a Formula Nippon race at Suzuka, with all the tactics running to script, leading the race after securing pole, I was just turning around to signal the crew that we were coming to the three-lap countdown to pit when we briefly lost track of where the car was. Then the call for the safety car came up on screen and there was the mental scrabble to decide to instantly come in as the window had just opened.

However, we let the driver know about this a sniff too late, missing the pit entry, and being thus condemned to have a lap behind the safety car. Ultimately this cost us seven places when the dust settled – but I did increase my vocabulary of swear words in French considerably, as the driver was not amused.

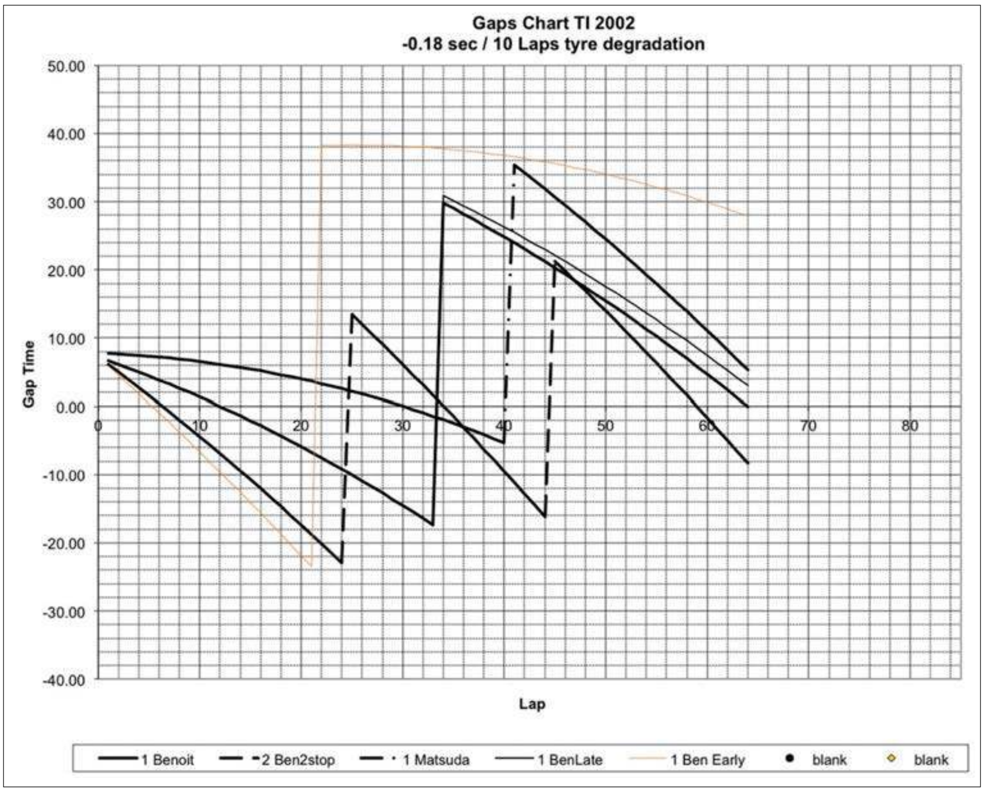

Figure 9: The tyre degradation and gap chart that helped formulate a very successful Le Mans strategy back in 2002

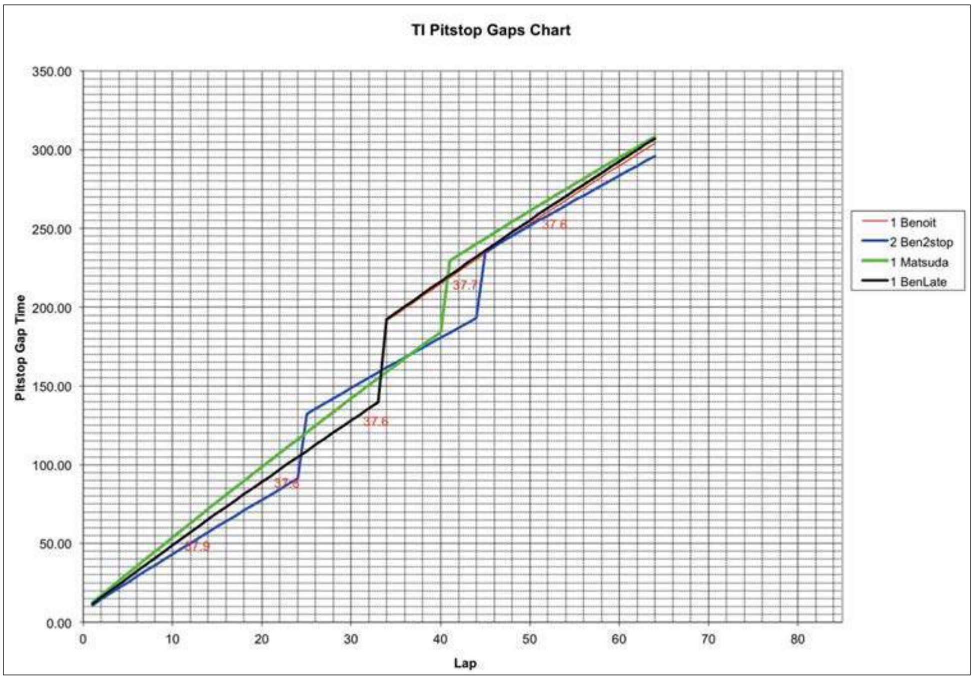

Figure 10: Part of the same Le Mans strategy as above – this chart covers those all-important pit stop gaps

There is, as usual, an endless amount of formats for your simulation. Our best ones were directly fed from the track timing system and our telemetry, with all the decision matrices pre-calculated, running on bespoke software with these inputs; car consumption, race position and also the same for the opposition. But it is always down to the engineer to make the radio call. Be sure of your data and simulation; there can be a lot at stake.

For engineers starting out in the business you can look at the above simple examples. They can be run on a spread sheet, maybe augmented by a few macros, and they will give you practice in automating your strategy. Remember, practice makes perfect.

Be careful, running your strategy at the race track in real-time can lead to wrong decisions through mistaken simulation assumptions


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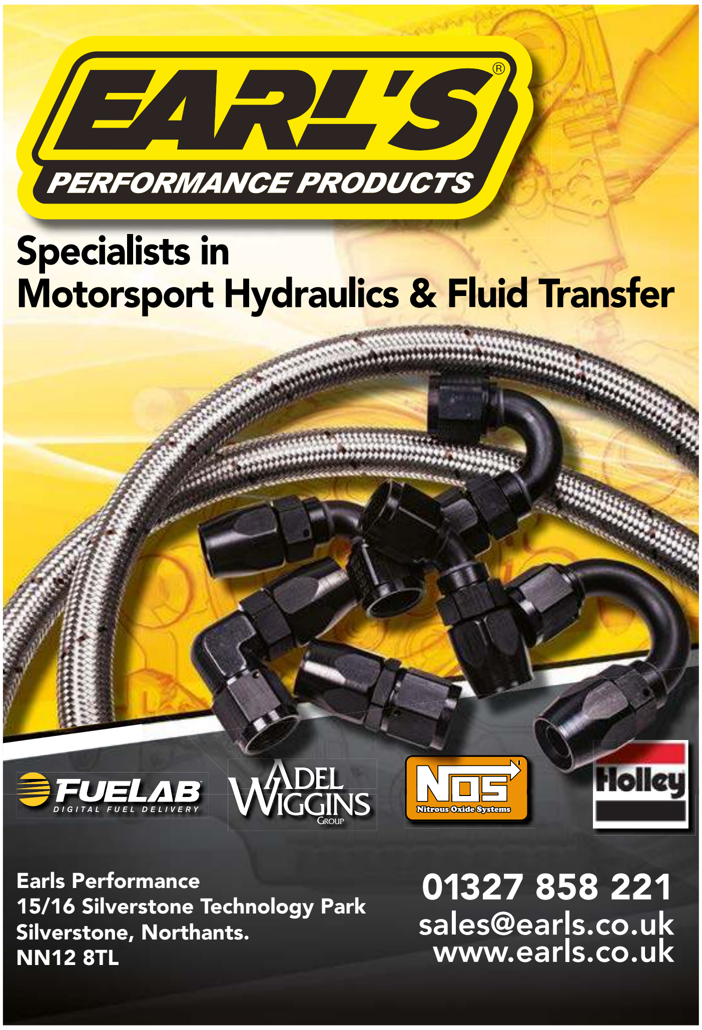
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Good vibrations: how to use a rig

Racecar's simulation maestro explains why shaker rigs are not only extremely effective but are also much less complicated to use than you might think

By DANNY NOWLAN

The closest a simulation gets to real life track action is probably when the actual racecar is strapped to a shaker rig. The car's wheels are worked through the pads

Some people in the industry tend to regard shaker rigs as either useless or far too complicated to use. Nothing could be further from the truth, and once you understand what a shaker rig is and how to employ it, you will realise it's actually one of the most powerful tools you will ever use.

Thanks to tools such as ChassisSim's lap time track replay and shaker rig simulation that I have developed, and by correlating this to shaker rigs that have been used by our customers, I have had a front row seat when this technology has been used in anger. The purpose of this article is to pass on the important lessons that have been learned along the way.

First things first, we need to understand what a shaker rig is. Basically, a shaker rig is a set of four hydraulic rams that are attached to the tyres that are able to vibrate the car at high frequencies.

From the picture (top) you can see there are further actuators to simulate downforce and longitudinal and lateral load transfer. The shaker rig has two important jobs. The first job is to explore the frequency behaviour of the car and the second is to replicate the tyre loads on track.

It will replay the tyre loads you'll get on track and then tune the car to minimise these loads and chassis attitude variations. Typically it will take logged race data and the inputs of the shaker rig will be tuned until you get correlation such as that which is shown in **Figure 1**.

Cooler shaker

Typically, the damper data will be taken and the road surface profile (bump profile in ChassisSim speak) will be reverse engineered from the data and the lateral and longitudinal accelerations will be used to drive the car actuators. The limitations of this are that because this is on a rig as opposed to the race track you don't get the same thermal environment for the car. That said, it gets you 85 to 90 per cent there.

Once you are on the shaker rig you play with dampers, springs, bump rubbers etc, as you would on the real car. You run the lap, look at the data and decide what to do, just as when you are at the track. Also you look at the damper and load data with very similar filters to what you do with track data in terms of minimising load and pitch and heave variation of the racecar. When you are finished you should find something that looks like **Figure 2**.

The baseline is coloured and the simulated is black. As can be seen from the improvement noted by the reduced oscillations, particularly at the rear, it is little wonder that you'll find a shaker rig on the premises of every F1 and NASCAR team.

But you need to be aware that shaker rigs are not perfect. As mentioned, the first shortcoming is that you're not replicating the track's thermal environment. This will make its presence felt in terms of tyre spring rates and to a lesser extent the thermal conditions of the damper.

Another limitation is that the downforce actuators are fundamentally limited by the control rate of the actuator. This means some high frequency stuff will be missed. The good news is these deficiencies are easily handled and they are by no means show-stoppers.

Once you are on the shaker rig you play with dampers, springs, bump rubbers and so on, just as you would with the car at the track

Figure 1: How to dial in the shaker rig

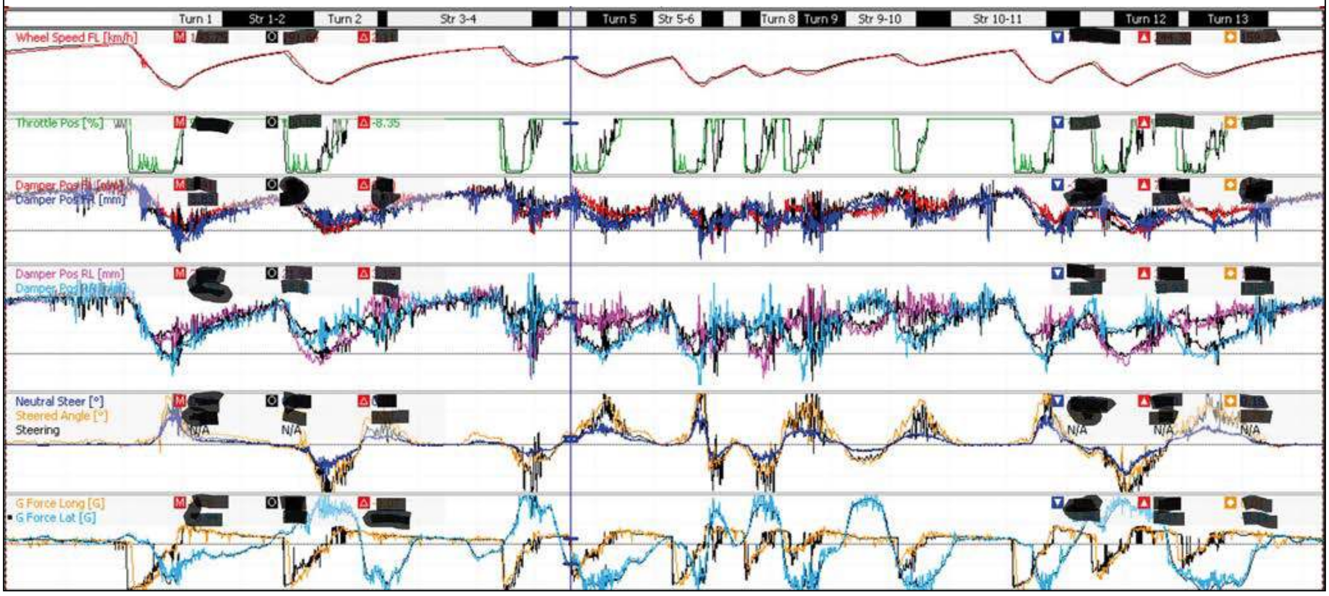
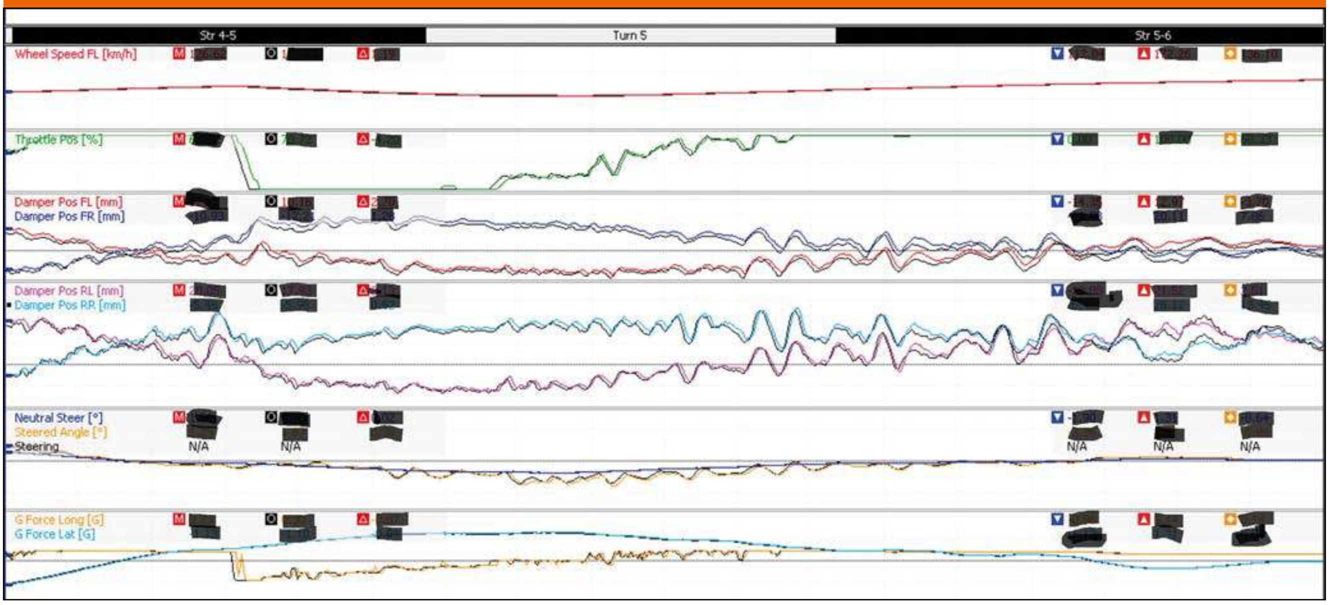


Figure 2: The end result of shaker rig tuning



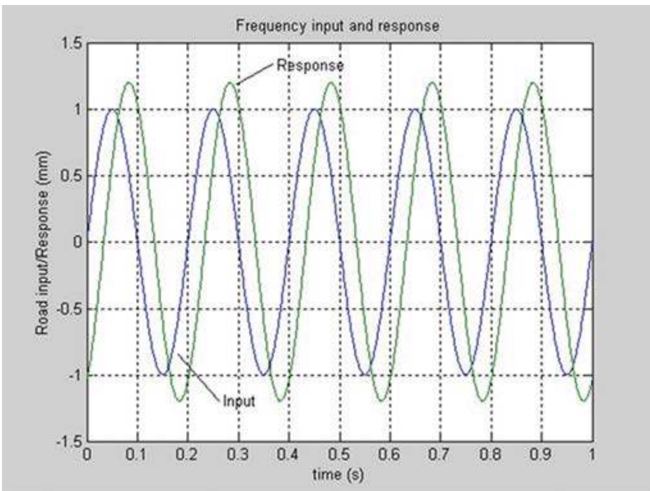
The big thing all this brings to the party is that because you are testing with the car you are testing with 95 per cent of the complete picture. In particular, the nuances of installation stiffness and spring hysteresis that require careful modelling are there right in front of you with a physical test. This makes this a very compelling reason to perform this type of test, and if you are focusing on minimising tyre load and pitch and heave variation you can't go far wrong.

Sine of the times

The second type of test is swept sine testing. Historically this type of shaker rig testing has always had a bad press. But once you understand what it is and where it comes from you can actually make good use of it.

What we measure with a swept sine test is the difference in amplitude and phase between

Figure 3: A typical frequency response



the road input and the racecar output at a given frequency. This is illustrated graphically in **Figure 3**. Here the blue trace is the input and the green trace is the car response.

As can be seen, there will be an amplitude difference and the signal will be slightly behind the input signal. This is referred to as phase lag. With this type of test for a given frequency we will express the amplitude variation as the ratio of output amplitude *vs* input amplitude and we will represent the phase lag as an angle.

The swept sine test is extremely useful because of how it will allow you to represent the signals in the frequency domain. Thanks to the work of the French mathematician Joseph Fourier, any signal can be represented in the frequency domain by **Equation 1**.

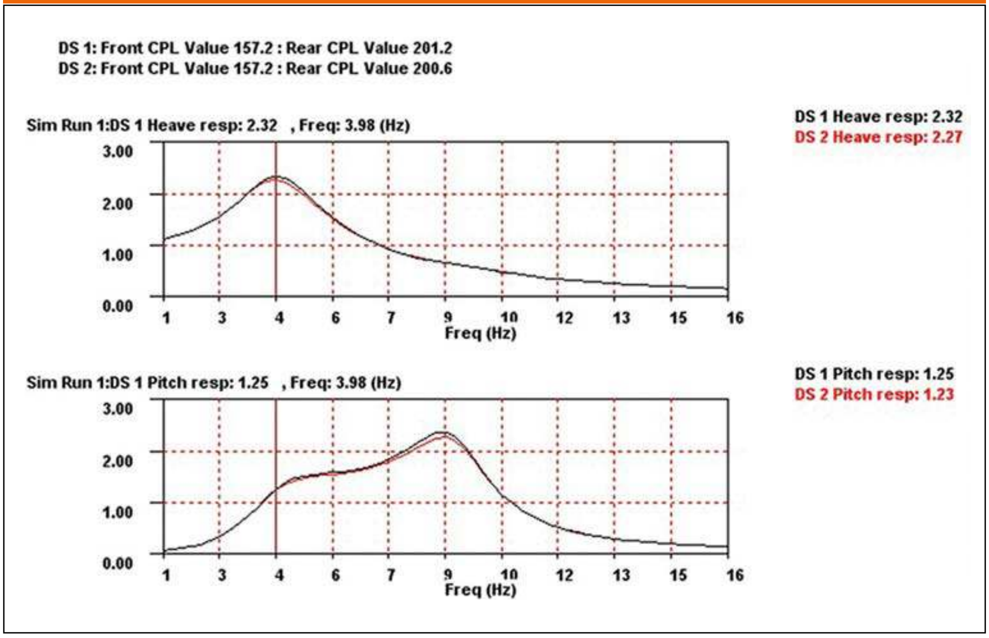
What the swept sine test does is it allows you to nail down the amplitudes and phase delays in a very precise way. Also, the other thing you get from a swept sine test is contact patch load variation. How you measure that will vary from rig to rig, but the approach in **Equation 2** is an excellent way to go.

This approach has served the ChassisSim shaker rig toolbox users very well. The important thing here is the lower this number is the better the contact patch load variation is.

All shook up

So what does the end result of a swept sine test look like? This is illustrated in **Figure 4**. The input mode here was the heave mode (which is typically the bulk of how swept sine tests are conducted) and this gives you the frequency plot of the heave response as a ratio of output/input *vs* frequency. On top of this, most of the time I will also look at the pitch cross response as well. Again this is output/input.

Figure 4: End result of a swept sine test



The swept sine test gives you valuable insights into the frequency behaviour

When you use a swept sine test you tread the fine line between minimising body response and contact patch load variation. So the list below has typically been the order of business when I, and my customers, have conducted swept sine tests:

- Note where the peak response is. This is the resonant frequency and it tells you what to look for in the data.
- Then you start playing with dampers and springs to minimise the contact patch load variation.
- After a while the contact patch load variation will level off.
- Then work on body response.
- Also, minimise the cross response modes – so if the input mode is heave you want pitch to be minimised.

The pitfalls

Like any tool there are a few traps here for the inexperienced. First, don't go silly on spring rates. I always limit myself to +/- 10 per cent from the base set-up. Remember, your selection of spring rates dictates mechanical balance and tyre heating and you vary from both at your peril. Also, for the swept sine test choose the aero loading appropriately. You are looking for the aero loading of the corner you are interested in.

In any swept sine test you also always tread a very fine line between minimising contact patch load variation and body response. As a rough rule of thumb, if mechanical grip takes precedence you favour contact patch load variation. Where aero is dominant, body response will be your goal.

Tuning for trends

Another point to consider is the correlation between simulation tools and actual shaker rig results. One of the things that I have found is that while the raw results have not been the same the trends have been identical. Consequently, that is what you are tuning a simulation model for. This is particularly apparent for the swept sine tests.

The other thing to point out here is that all the above has been used in anger at the track. As a case in point my Australian dealer Pat Cahill used the shaker rig toolbox to engineer the Maranello Motorsport Ferrari F458 entry to victory at the Bathurst 12 hours in 2014. Also, on a personal note, the shaker rig toolbox played a significant role in the damper specification of the NA Autosport entry I engineered at World Time Attack challenge at Eastern Creek in 2016.

In closing, in both track replay and swept sine mode the shaker rig offers very powerful insights and tuning tools for the racecar. With the track replay mode it gives you an excellent way to minimise body and contact patch mode response. The swept sine test gives you valuable insights into the frequency behaviour of the car that tells you what to look for, and when used properly this is a powerful race-proven tuning tool. What more could you ask for?

EQUATIONS

EQUATION 1

$$y = \sum_{f=0}^{\infty} A_f \sin\left(2 \cdot \pi \cdot f \cdot t + \phi_f\right)$$

Where:

y = output
t = time
A_f = amplitude of that frequency
f = frequency in Hz of the signal
ϕ_f = phase delay of the signal in radians

EQUATION 2

$$CPL = \frac{\Delta Load}{\Delta acc_{input}}$$

Where:

CPL = contact patch load variation (kg)
$\Delta Load$ = change in load in N from equilibrium condition
Δacc_{input} = amplitude of acceleration signal

Interview – Dick Bennetts

Triple crown

The WSR team boss explains how his BMW-running outfit overcame the odds to win all three of the main BTCC titles in 2018

By MIKE BRESLIN

'Why is it that every year when a rear-wheel drive car wins it gets penalised, but when a front-wheel drive car wins it doesn't get penalised?'

Question: what has Colin Turkington in common with Keke Rosberg and Mike Hawthorn? Answer: winning a championship with just one race victory. In fact, Turkington's 2018 BTCC title success is even more extraordinary than Rosberg's 1982 and Hawthorn's 1958 championship triumphs, as they were from 16 and 11 grands prix respectively, while the BTCC is a 30-race season.

But then the BTCC is a vastly different place to Formula 1 in any era; you never have had and never will have 17 different winners in Formula 1, as the BTCC did in 2018, for a start. This amazing statistic was largely down to the success ballast that's an integral part of the BTCC, but this has also meant that winning the championship is possibly more about consistency than it is about speed these days.

Indeed, Dick Bennetts, the boss of BMW UK's appointed team, West Surrey Racing, which won the drivers', manufacturers' and teams' titles in 2018, says of his outfit's triple triumph: 'We didn't have the fastest car, but with Colin being Mr Consistent, having a very good car at most of the tracks, and getting points at each round, we kept plodding away. But winning the championship with only one win just shows his consistency, and his ability to keep out of mischief. Also, we mustn't forget Andrew [Jordan] Rob [Collard] and Ricky [Collard] as they also contributed a lot to the teams' and manufacturers titles'.

Unfair advantage

Yet while the fact that there were 17 winners might suggest all is well with the BTCC in terms of the performance balance between the cars, Bennetts believes that some cars are a little more equal than others, namely the Subaru Levorg, which he says came to the party with an inbuilt design advantage.

'The bottom line is that that car has got an unfair advantage due to its engine position,' Bennetts says. 'Even though there is a CoG weight equivalency factor calculated by RML [technical partner to the BTCC] , it doesn't appear to be working correctly. That needs to be rectified for it to carry on, as almost everyone down the pit lane knows it's not right. The car is just so superior in damp and wet conditions. The engine is down so low and back so far it's like a mid-engine sportscar!'

Of course, there's nothing wrong in choosing a base car for a motorsport campaign that will hopefully give your team an advantage, that's part of the game – it's up to the series to police this. In fact, WSR itself also chose the BMW 1 Series, back in 2012, with thoughts on its possible advantages.

'Being a small car, the BMW 1 Series was light, so therefore we could get good weight distribution,' Bennetts says of the car it still uses in the series. 'But then the powers that be have penalised us, so that advantage went out the door, and that is another question I have: why is it every year when a rear-wheel drive wins they get penalised, but every year a front-wheel drive wins they don't get penalised?'

Some might say this is because rwd has an inherent advantage – it's no accident that all full-on racecars are rear-driven – but Bennetts says this is not so much the case anymore. 'The Dunlop race tyres are very good now,' he says. 'They don't get the degradation that they used to, so you can run the diff with more preload. If you ran the diff with too much preload years ago you would just destroy the tyres. You would qualify with it, which we used to do with the front-wheel drive MG [from 2001 to 2006], but then you had to soften the diff off for racing. With the tyres now, they can run a lot of preload, which enables a front-wheel drive to brake later and get better traction. So the perceived advantage of a rear-wheel drive car being quicker off the corner, those days are gone.'

Back to front?

All this might become a thing of the past for WSR if it switches to front-wheel drive, though, and at the time of writing this is a possibility with BMW bringing out a front-drive 1 Series in 2019. Right now a decision over whether to race it in this configuration has yet to be made.

This is WSR's call, for while it is nominally the 'manufacturer-assisted' BMW team, Bennetts is keen to stress that this label does not carry the weight of a full works effort. 'We are not a BMW factory team,' he says. 'We were a full-on factory team when we ran the [Ford] Mondeo, [Honda] Accord and the MG ZS, as they paid for everything.'

So what does BMW bring to the programme now, then? 'They bring technical expertise and they paid to develop the new engine [the B48 introduced in 2017],' Bennetts says.

The rest of the budget is found through sponsorship deals, Bennetts tells us, but certainly not through prize money. 'In the drivers', teams' and manufacturers' championships there's no

prize money,' he says. 'Dunlop do supply a prize fund and some tyres, if you win the privateers division, and as a manufacturer entry you get some tyres if you win the manufacturer division.'

Yet while there might not be much in the way of prize money there is the knowledge that you're competing in a very successful championship with live TV coverage and very large spectator attendances, plus technical regulations in the NGTC that, on the whole, have been very successful. 'The NGTC is a good formula, as when a team wants to upgrade, or build new cars, many of the major components carry over to the new build. Also, the TBL system [the specific BTCC licence that's allocated to each and every car] puts a real value into the second-hand cars and the teams themselves,' Bennetts says.

Hybrid future

The NGTC regulations have helped keep things very stable in the BTCC over recent years, but there is change on the horizon. The new set of technical regulations, set to come in for the 2022 season, will possibly include some form of hybrid element to the power unit. It's moving with the times, but Bennetts believes it will need to be careful in the way it goes about this. 'It will happen,' he says. 'But it must be cost effective, because proper budgets are hard to find now. Hopefully, with going hybrid, it will encourage new sponsors to join the BTCC.'

Then there are other factors to consider, too. 'It depends on what type of hybrid, to be honest,' he adds. 'You can have an electric motor in several different ways; you can have pure hybrid, you can have a high voltage battery … But then you're into a different league; the marshals, staff, etc. would need to be trained, so the cost goes up again. I like the principle of it, but how it will be executed, I'm not sure yet.'

One thing he is sure about is staying in the BTCC. The team has been a stalwart of the championship for over 20 years now, since switching from Formula 3 for the 1996 season – a category in which it was hugely successful, running drivers such as Ayrton Senna, Mika Hakkinen, Rubens Barrichello and Jonathan Palmer – and Bennetts, despite some frustrations, sees no reason to switch to another series anytime soon. 'At the moment the BTCC is a great championship; live television, big crowds, and it's very, very competitive,' he says. 'Now, at my stage of life, I enjoy the competitive and close racing of touring cars.'

WSR topped the drivers', teams' and manufacturers' (for BMW) standings in the BTCC in 2018

RACE MOVES

XPB

The Supercars series has appointed **Adrian Burgess** as its new head of motorsport, a role that will see him overseeing the future technical and sporting direction of the premier Australian motorsport category. The former mechanic, engineer and team principal, who has worked in Formula 1 in the past, has been involved in Supercars since 2006, usually as a team manager. He replaces **David Stuart** in the role, the latter having accepted a position with the Confederation of Australian Motorsport (CAMS).

Taylor Kiel is now general manager at IndyCar outfit Schmidt Peterson Motorsports (SPM), having been promoted from the post of team manager. Kiel succeeds **Piers Phillips** in the position, the latter having left SPM after three seasons with the team.

Piers Phillips (see above) is now team president of Rahal Letterman Lanigan Racing (RLL). He will now oversee RLL's operations in IndyCar, IMSA and the Jaguar I-PACE eTrophy. Phillips has an extensive background in touring cars and sportscars, including running teams at the Le Mans 24 hours.

Damian Meaden is the new PR manager for the British F4 Championship. Meaden comes to F4 from Formula Renault NEC, where he was PR officer, while he has also worked as a motorsport journalist covering a wide range of national and international series, including the British Touring Car Championship. He replaces **Alex Battipaglia** in the post, the latter having moved on to work at McLaren.

Sabre Cook (24) a mechanical engineering student from Colorado University is the Infiniti Engineering Academy 2018 USA winner. Her prize is a six-month work placement at the Renault F1 base in Enstone in the UK, followed by a further six months at Infiniti's Technical Centre Europe in Cranfield, also in the UK.

IndyCar team co-owners **Jimmy Vasser** and **James Sullivan** are to enter a new Lexus-running squad in the IMSA Sportscar Championship. The pair, co-entrants of the Dale Coyne Racing No.18 car in IndyCar in 2018, will team up with AIM Autosport to take over running the IMSA Lexus RC Fs from the **Paul Gentilozzi**-owned 3GT Racing team. The squad is to be called AIM Vasser Sullivan.

Ferrari F1 boss **Maurizio Arrivabene** dedicated **Kimi Raikkonen's** win at the US Grand Prix to engineer **Daniele Casanova**, head of performance simulation for Ferrari, who died after suffering a cardiac arrest in October at the age of 48. Casanova had had a long career in Formula 1, having previously worked at Renault, Toyota, Red Bull and Lotus before joining the Scuderia.

James Barclay, the director of the Jaguar Formula E operation, has succeeded **Roger Griffiths**, the head of the BMW Andretti team, as the chairman of the recently renamed Formula E Teams and Manufacturers Association (FETAMA). Originally called FETA, the teams' organisation was set up in Season 1 (2014/15), with Mahindra boss **Dilbagh Gill** its first chairman.

Scott Graves will be crew chief on the Roush Fenway Racing-run No.6 Ford, driven by **Ryan Newman**, in the NASCAR Cup Series in 2019. Graves was, until early October, the crew chief on the Joe Gibbs Racing No.19 Toyota driven by **Daniel Suarez**. He replaces **Matt Puccia**.

Cobra Sport Exhausts managing director **Rachel Abbott** will take on a joint team principal role alongside AmD Tuning boss **Shaun Hollamby** in the BTCC in 2019, to help run the Honda Civic Type Rs that previously belonged to Eurotech Racing under the Cobra Sport AmD Racing banner. AmD has bought the TBLs (the TOCA BTCC Licences, which are needed to compete in the series) that belong to the two racecars.

Meanwhile, **Hollamby** (see above) will also act as joint team principal, alongside **Andy Wilmot**, at the new Trade Price Cars Racing set-up. Trade Price managing director **Dan Kirby** has bought two Audi S3s along with their TBLs from AmD, but Hollamby's organisation will continue to run the cars. Former BTCC and Renault UK Clio Cup driver Wilmot joins from Matrix Motorsport.

Rob Smedley to step down from performance engineering role at Williams

Rob Smedley will no longer be a part of the Williams Formula 1 operation as it goes into the 2019 season, having decided to leave the team at the end of 2018.

XPB

Rob Smedley is to leave Williams after working with the F1 team for four years

Smedley has been head of performance engineering at Williams since 2014, when he joined the Grove outfit from Ferrari, and his departure comes at the end of a difficult year for Williams, which has languished at the foot of the championship table for much of the season. Other high profile figures have also left the team throughout the year, with Dirk de Beer (head of aerodynamics) and Ed Wood (chief designer) leaving in May.

Smedley's Formula 1 career started 17 years ago with Jordan and he then went on to join Ferrari in 2004. At Williams he helped the team to back-to-back third-place finishes in the constructors' championship in 2014 and 2015 and then fifth place in 2016 and 2017. To begin with he was in charge of the Williams pit wall at the grands prix, but then he took on broader technical responsibilities.

'I have thoroughly enjoyed my time at Williams,' Smedley said. 'The team has been through great change since I joined in 2014 and it has been a pleasure to have played a part in that. Williams is a very special team within the F1 community and I'm certain that with all the talent that we have here they will go on and do better things. The team will always remain close to my heart. After 20 years in F1, however, I feel it's the right time to reflect on things and evaluate what the next move is.'

Claire Williams, deputy team principal at Williams, said: 'It's been a pleasure having Rob in our team and we will miss him both personally and professionally. He agreed to join us at a time when our performance was low, and we are grateful that he saw the potential for us to turn things around at that time.'

OBITUARY – Mari Hulman George

Mari Hulman George, the chairman of the Indianapolis Motor Speedway (IMS) and Holman & Company – owner of the fabled race track and the IndyCar Series – from 1988 until 2016, has died at the age of 83.

Hulman George's father, Tony Hulman Jr, saved the speedway from almost certain demolition after World War II, when he bought the facility, but she was much more than just an heir to the family business; she was also a successful race team owner in the 1950s and 1960s, while beyond racing she was a well-known philanthropist, particularly in the spheres of the arts, healthcare and animal care.

For decades, Hulman George hosted the famous 'Racers Party' on the opening weekend of the Month of May – the prolonged qualification process for the Indianapolis 500 – while she was perhaps best known for the 'gentlemen start your engines' order she delivered every year before the great race.

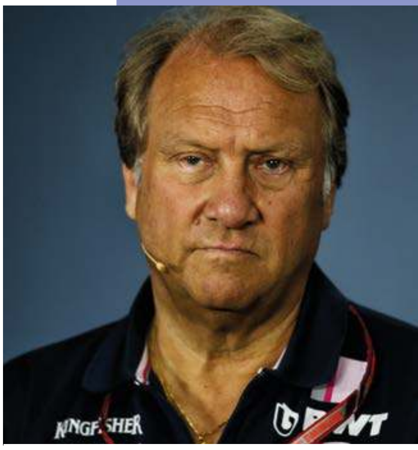
During Hulman George's time in charge at IMS she expanded the track's activities to also include the Brickyard 400 NASCAR Cup race and, for a few years, both Formula 1 and MotoGP events.

Mark Miles, CEO of Hulman & Company, said of her passing: 'Mari Hulman George was one of the nicest, most gentle people you would ever meet, but she also was an incredibly influential leader in American motorsports and the state of Indiana for the last 60 years.

'She combined a true passion for auto racing with a common, human touch toward all, especially drivers and fans. Generations of Hoosiers [as the people of Indianapolis are known] have benefited from her tireless charitable work, and her commitment to animal care is exemplary and a mirror of her kindness,' Miles added. 'We extend our sincere condolences to the entire Hulman-George family and will miss her greatly.'

Mari Hulman George 1934-2018

RACE MOVES – continued



XPB

Bob Fernley, the former deputy team principal of the Force India Formula 1 team, has been appointed president of McLaren's Indy 500 effort, which will facilitate **Fernando Alonso's** return to the brickyard in 2019. Fernley, who left Force India after its takeover during 2018, has past experience of IndyCar, having been involved with Ensign back in the 1980s. He has been tasked with building and leading a team for the 2019 race while also helping to evaluate 'longer-term McLaren involvement in IndyCar'.

Seven-time Supercars champion driver **Jamie Whinchup** has bought a 15 per cent stake in the Triple Eight Race Engineering team, the outfit he has driven for since 2006, joining **Roland Dane**, **Tim Miles**, **Paul Dumbrell** and Dane's daughter **Jessica** as partners in the organisation.

International Speedway Corporation (ISC), the track owning and operating arm of NASCAR, has promoted **Julie Giese**, its managing director of business operations, design and development, to the post of president of the redeveloped ISM Raceway in Arizona.

Chris de Coninck has replaced **Daniel Grunwald** as **Daniel Abt's** race engineer at the Audi Sport ABT Schaeffler FE operation for season 5 of the all-electric championship. De Coninck worked with **Maro Engel** at Venturi last season.

David Clarke is the new team manager at the DS Techeetah Formula E operation after replacing Andretti-bound **Campbell Hobson**. Clarke has previously held posts at Mercedes-Benz, McLaren and at the HWA DTM operation.

Also at DS Techeetah (see above), **Fabrice Roussell** has moved to a wider-ranging engineering role. Roussell engineered **Andre Lotterer** last season but has now been replaced in that position by **Andreas Siegfried**.

Ron Ruzewski is now the managing director at Team Penske. Ruzewski, who will report directly to team president **Tim Cindric**, will oversee Penske's IndyCar and IMSA teams in a new role that's been created ahead of the retirement of long-time Penske executive **Clive Howell**, who leaves at the end of 2018 after 39 years with the organisation.

Ryan Story, the managing director of the DJR Team Penske Supercars squad, has been voted on to the Australian series' rule-making Commission. Story takes the position of the alternate Commission member. This was previously filled by Garry Rogers Motorsport director **Barry Rogers**. The Commission makes recommendations to the Supercars board on racing rules and regulations. It's made up of an equal number of team and series representatives.

NASCAR Cup crew chief **Chad Johnston** was fined $25,000 after the No.42 Chip Gannasi Racing Chevrolet he is responsible for was found to have been running with damaged parts reattached to the car in a way that contravened the regulations. Car chief **David Bryant** was suspended from one Cup race for this transgression, which was discovered at the Talladega round of the series.

◆ Moving to a great new job in motorsport and want the world to know about it? Or has your motorsport company recently taken on an exciting new prospect? Then email with your information to **Mike Breslin** at **mike@bresmedia.co.uk**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Show business

With just a matter of weeks until the Autosport Engineering show the excitement within the industry is beginning to build

It's less than a month before Europe's largest motorsport trade show rolls into the Birmingham NEC. The Autosport Engineering Show, held on January 10-11, 2019 sees more than 250 of Europe's finest technically advanced companies coming together under one roof ahead of the start of the international and national racing seasons.

The entire show is to be housed in new halls and is therefore sure to have a different feel to it this year. Autosport Engineering will be housed in Hall 3A of the NEC's Piazza complex, and within that *Racecar Engineering's* editorial and advertising team will be found on stand E405. We will have the very best subscription offer available for the year, so make sure you come and find us.

The Engineering show will be a platform for suppliers to showcase the latest technologies across motorsport, automotive, aerospace marine and defence sectors. This is a dedicated show for the world's biggest and most successful organisations and networks, with global business leaders and trade stakeholders within a professional B2B environment.

With 62 per cent of visitors actively coming to the show to look for new products, Autosport Engineering is primed to be the place to kick-start the 2019 motorsport season, with a host of exhibitors launching new products to a truly global audience.

This is also the final Autosport International Show to be held before Brexit, which is set for March 29, so it is a good chance for those companies that trade internationally to sign deals that will help to ensure a smooth transition through this challenging period.

The wider event

In the four-day main show, Autosport International (January 10-13), celebrated this year will be 50 years of Formula 5000. This will be honoured by the Historic Sports Car Club, which will feature cars from Lola, McLaren and Surtees. Also in the spotlight will be the World Rally Championship, which on the Saturday will launch its 2019 season. The presentation will see each of the manufacturers competing in the WRC – Ford, Hyundai, Toyota and Citroen – unveiling their 2019 contenders.

For those more interested in the online community, the show will host the fourth round of the Le Mans Esports Series. Competitors have the chance to win a share of US$100,000 and also a coveted spot on the Le Mans podium through this competition.

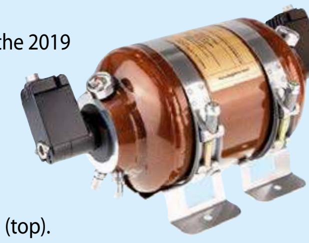
More than 250 of Europe's most technically-advanced companies will come together under one roof ahead of the start of the racing season

Featured at ASI

Greenpower Education Trust

The Greenpower Education Trust, which is in to its 20th year, continues to promote education in sustainable engineering and technology for young people across the globe. The Greenpower challenge to design, build and race a single-seat electric car provides young people with a unique, hands-on opportunity to engage in engineering. The Education Trust's aim is to demonstrate the importance of engineering to solve problems faced by societies, particularly involving sustainability, and to help address the UK's need for 830,000 new engineers by 2020.
Stand E181 www.greenpower.co.uk

Lifeline



In readiness for the 2019 season, Lifeline Fire and Safety Systems has developed a range of new safety harnesses (top). This new product line up from Lifeline will be available in a variety of styles to suit both clubman and professional drivers.

The UK-made harnesses feature a unique Lifeline designed buckle with a positive and reassuring action and a high degree of finish, along with high quality adjusters to ensure ease of adjustment without slip and a choice of end fittings for easy installation.

Also from the company is a new fire suppression system, the 8865 (above), which weighs less than 3.5kg, including all of the installation ancillaries. The filled cylinder itself only weighs 2.6kg. Designed to knock down fire in the engine bay and cockpit simultaneously, Zero 275 is perfect for competitors seeking to save weight, cost, complexity and packaging, with increased fire protection when compared with previous generations of 8865 systems, we're told.
Stand E722, www.liferacing.com


Zircotec has proven its heat management products in motorsport

Zircotec

Regular show exhibitor Zircotec has grown exponentially thanks to support from the Advanced Propulsion Centre in the endeavour to generate a carbon neutral agricultural tractor. The development of the Zircotec Technical Department has enabled improvements and developments in the majority of its processes, offering a more refined and adaptable service to the automotive industry as a whole.

The increased supply chain in the industry results in not only a significantly increased piece part cost, but also adds mounting pressure on the JIT (just in time) scheduling requirements on both Tier 1 and OEM production lines. In order to address this issue, Zircotec has been working towards the development of both alternative products that can offer the right heat management properties without the need of shipping, as well as an industry first venture to create solutions on the premises for partner OEMs and Tier 1 suppliers.
Stand E488, www.zircotec.com

Essential Equipment Consortium

Essential Equipment Consortium (EEC) Performance Systems has designed a fuel bowser that can deliver or receive fuel with accuracy and reliability. EEC works with race teams in the motorsport industry and it has ensured it meets all criteria required by them and race organisers to be used in the sport.

EEC has also developed an ATC (Automatic Track Compensation) system, ensuring that the bowser is accurate for all race circuits around the world. Unique software has been devised, which ensures accurate delivery of the fuel required in all states.

The range of bowsers have been rigorously tested by race teams over the past few seasons with customers in F2, WSR 3.5, WEC, British GT, Blancpain, CTCC and Formula 1.
Stand E342, www.eec-ltd.com

Race Winning Brands Europe

Race Winning Brands Europe has become an official distributor of ZRP products (above) and will offer its full line of connecting rods and crankshafts. The company will now supply all ZRP connecting rods and crankshaft catalogue part numbers to European enthusiasts and customers.
Stand E512, www.racewinningbrands.eu

Intercomp

Intercomp's Precision Hub Scale System allows engineers and mechanics to remove inconsistencies with wheels and mounted tyres that can affect the optimal set-up on a racecar.

The Hub Plate Scale System, the industry's first alignment system with an integrated wireless scale in the hub stand, is said to be a solution that allows for consistent scale values without the need for dedicated tyres and wheels for the scales. Hub stands for the system, which are made of 6061-T6 aircraft-grade billet aluminium, pair superior materials and engineering with 360-degree ball transfer bearing technology, which allows the suspension to settle without binding.
Stand E432, www.intercompracing.com

Clarendon Fasteners

Clarendon Specialty Fasteners will be at Autosport Engineering showcasing the latest fastener technology from its AeroCatch 3 range. The fasteners offer an aerodynamic, high strength tension latch for securely fastening panels together with the added feature of a shear engagement tongue allowing the latch to carry loads in three axis, we're told. Traditional surface mounted latches are used in recessed pockets in an effort to improve air flow and aesthetics, but this eliminates this expensive and time consuming process and only requires a simple panel cut-out procedure for installation.
Stand E562, www.clarendonsf.com

Lane Motorsport

Lane Motorsport will showcase its most comprehensive electronics connector and accessory package to date. Based around the industry leading Souriau 8STA Series, the company's range of connector accessories from Hellermann Tyton and Weald Electronics is designed to not only handle the most extreme environments, but also to save time and money during assembly, installation and replacement. Together, these products complete a comprehensive motorsport interconnection package.
Stand E760, www.lanemotorsport.com

Ticket information

www.autosportinternational.com

AUTOSPORT INTERNATIONAL ENGINEERING SHOW

The two dedicated trade days, the Autosport Engineering Show, are on Thursday 10 and Friday 11 January. These are exclusively reserved for people who are involved in the industry or those studying for a motorsport or engineering related qualification.

Discounts are available for MSA (now known as Motorsport UK) members. Advance trade tickets can be purchased from £30, and £25 for MSA members. Please visit the website for details and for tickets for the four-day Autosport International Show.

TEST EQUIPMENT
A&D's Spintron Controller upgrade

A&D Technology now offers an update to Trend Performance's Spintron test system. This includes a new Windows 10-compatible user interface, a controls system based on A&D's iTest software platform, new modular I/O and a Phoenix Combustion Analysis system for high-speed laser data acquisition.
www.aanddtech.com

COMPOSITES
Carbon copy

Swiss hi-tech firm Bcomp has gathered the latest composites and light-weighting knowledge and applied it to natural fibres.

Thanks to its proprietary PowerRibs reinforcement technology, natural fibres can replace carbon fibres for high-performance applications such as motorsport bodywork, reducing costs by up to 30 per cent, and improving vibration damping and safety. It can be combined with AmpliTex for full NF layup or carbon for extreme performance.
www.bcomp.ch

PRODUCT FOCUS: RACEWEAR
Sparco McLaren SP16+

McLaren Automotive is known for its continuous pursuit of light weighting technology. Following that thread, a must-have item for McLaren fans, racers and track-day drivers alike, the Sparco McLaren SP16+ is a race suit designed like no other. With the whole suit weighing at least 10 per cent less than any other, the Sparco McLaren SP16+ is the lightest race suit yet approved by the FIA at just 590g (size 52). Worn by McLaren F1 Racing Team drivers since 2016, this ground-breaking suit can now be ordered by McLaren Automotive customers and purchased for £2344.

As with the Formula 1 race suits, the Sparco McLaren SP16+ is entirely hand-made in Italy, each suit taking more than 12 hours to complete. The suit can also be personalised to order, with a selection of bespoke colours and options including side pockets, phone pocket and belt.

The SP16+ features an ultra-slim zip, seamless Nomex wrists and ankles, reduced neck and shoulder pads and ultra-thin thread for the stitching – which have all played their weight-saving role, some decreasing the suit's mass by mere micrograms at a time.

A special two-layer construction of fireproof material reduces weight even further, while ensuring the garment remains exceptionally breathable and comfortable to wear.

Like McLaren, Sparco was founded by racing drivers with a passion to advance their sport. Determined to revolutionise driver safety in Formula 1, the drivers from Turin introduced their first fireproof suit in 1977. In the 41 years since, they have constantly innovated to combine the highest safety standards with the distinctive Italian style for which Sparco products are known.
cars.mclaren.com

Left: Bruno Senna models SP16+ suit

DYNOS
Dimsport on a roll with its all-new power bench tester

Dimsport's new Dynorace A2CTION power bench tester has been designed and developed to support the latest vehicle technology, we're told. The result is a 4WD braked dynamometer – also available in Active configuration – which comes with a single roller frame and a rigid connection between the front and the rear axle (thanks to a driveshaft).

This platform has been conceived not only to brake the acceleration of the car (simulating load conditions/uphill roads) but also – when provided in Active configuration – to accelerate the rotation of the wheels (simulating downhill conditions and for hybrid/electric vehicles, testing while recharging the batteries). In short, a clever bit of kit.
www.dimsport.it

SIMULATORS
New machining behind Greaves 3D snorkel vents

Greaves 3D has now put its very latest fuel rig snorkel vents into production and they will be ready for the 2019 season.

The British-based company now uses the Mazak VTC 760 C with on-board HyperMill Cam software to ensure that it keeps up with advances in the engineering sector. Opting for the vertical travelling column machining centre, Greaves 3D is now ready for a wider variety of jobs, it tells us.
greaves3d.com

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Clear and present danger

There was a chill that descended on to the press room in Macau as the first images of Sophia Floersch's F3 car having cleared the catch fencing at Lisboa came in. We all knew this was a high speed impact, but then the images of the accident were shared on social media, and the full extent was clear. One journalist who saw the accident was almost in tears, and said 'you don't want to see it.' He was right, I didn't, but everyone was on their phone, watching it, and displaying various emotions, including shock to sadness, so it was a bit difficult to ignore.

Then the news started to filter through; she was alive, and conscious. Given the severity of the accident, that was blessing enough. That she has had surgery for a spinal fracture is still a worry, although the injuries to the marshal and the photographers that were caused either by falling down the stairs at the back of the structure into which she ploughed or when the roof lining that came down on them, were mercifully few.

Then the predictable aftermath. Jean Todt issued an ominous tweet that, given the conversations already had in the paddock over the preceding days, seemed a foregone conclusion. 'We will monitor the situation and make the necessary conclusions,' wrote the FIA president, while also wishing all involved a safe recovery.

Many of the drivers who were at Macau for the first time spoke of the awe they felt for the place

The problem, as I wrote last year, is not the circuit, or the event. At Macau precision is key, and many drivers who were at the race for the first time spoke of their awe for the place; one even said he had found a new favourite circuit. This is a track where you have to be precise, and if you make a mistake, you crash. Sometimes heavily.

The involvement of the FIA through the World Cup, both in GT and Formula 3, was always going to shine a light on this, a street circuit with such long straights that, under the SRO's four-class system of grading circuits, is up there with Monza. Augusto Farfus gave Schnitzer team manager Charly Lamm a perfect send off with wins in the GT races, simply by applying the power out of the Melco hairpin that gave Mercedes no chance to attack into Lisboa, pretty much half the track away and pretty much flat out throughout. Normally there would have been a conversation about BoP, but this was Charly's last race, and no one was about to pour cold water on this man.

However, the conversations with team managers in both paddocks highlighted that the FIA did not want to be here. The questioning then turned towards what would happen if their involvement ceased. Macau organisers have said that they will work with the FIA on track safety, but would people still want to come and race here without the cache of a World Cup title? The answer was pretty much; yes. After last year's multi-car pile up, GT teams found it difficult to insure their cars, and many raced without it. Perhaps that was part of the reason for the drivers' surprising restraint (yes, I do know that Laurens Vanthoor once again came a cropper in spectacular fashion at Mandarin and wrote off his Porsche).

This is a track which rewards good driving, and Dan Ticktum dominated the weekend. Yet, the future of Formula 3 at the track is also in doubt. There will be a change soon and this will be discussed in forthcoming issues of *Racecar*, but with an international Formula 3 car built by Dallara and presented at the last GP in Yas Marina late in November, and a new regional Formula 3 car produced by multiple manufacturers, which will be allowed to race at Macau?

The FIA F3 World Cup will, I assume, require the new international car from Dallara, but the company is only geared up to selling 30 of these, so not enough to fulfil the requirements at Macau. Also, the cars should be faster than the old cars in which Floersch had her accident. For that to happen, almost certainly the FIA will require a new homologation to the track. Having sat through the immediate aftermath and shock of Floersch's accident, and so by no means taking away anything from the severity of the crash, I still maintain that this is a circuit that should not have its character removed by false chicanes installed to reduce the awesome Mandarin, or the skill of picking a braking point at full speed in a racecar, or on a motorbike. This is a circuit that is the antithesis of the modern grand prix circuits, so anaesthetic in nature, and in some way that must be preserved.

While Gabriele Tarquini was fighting for his World Touring Car title, aged 56 by the way, he started the second race in 14th place and was involved in a melee at Lisboa that meant he failed to score points. He started the third race, also in 14th place, but rather than complain about the casino on track, he accepted that this was part of the game. He did win the title, by three points from Yvan Muller, and celebrated in style. I look forward to someone beating him, not because I dislike him, but because to be considered worthy, you have to beat the best. I take my hat off to him, and to everyone who raced at Macau. I hope to see you all there again next year.

ANDREW COTTON Editor

Serious Horse Power

Now Capable of Billet Machining

The new EM "Engine Machining" CNC Machining Centers are built on Rottler's 95 years of design and manufacturing experience. We are dedicated to providing customers even more flexibility for engine parts machining, digitizing and porting, and custom parts manufacturing, making Rottler EM Machining Centers the most technically advanced industry-specific system to date.

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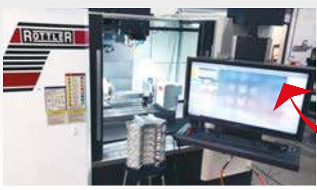

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