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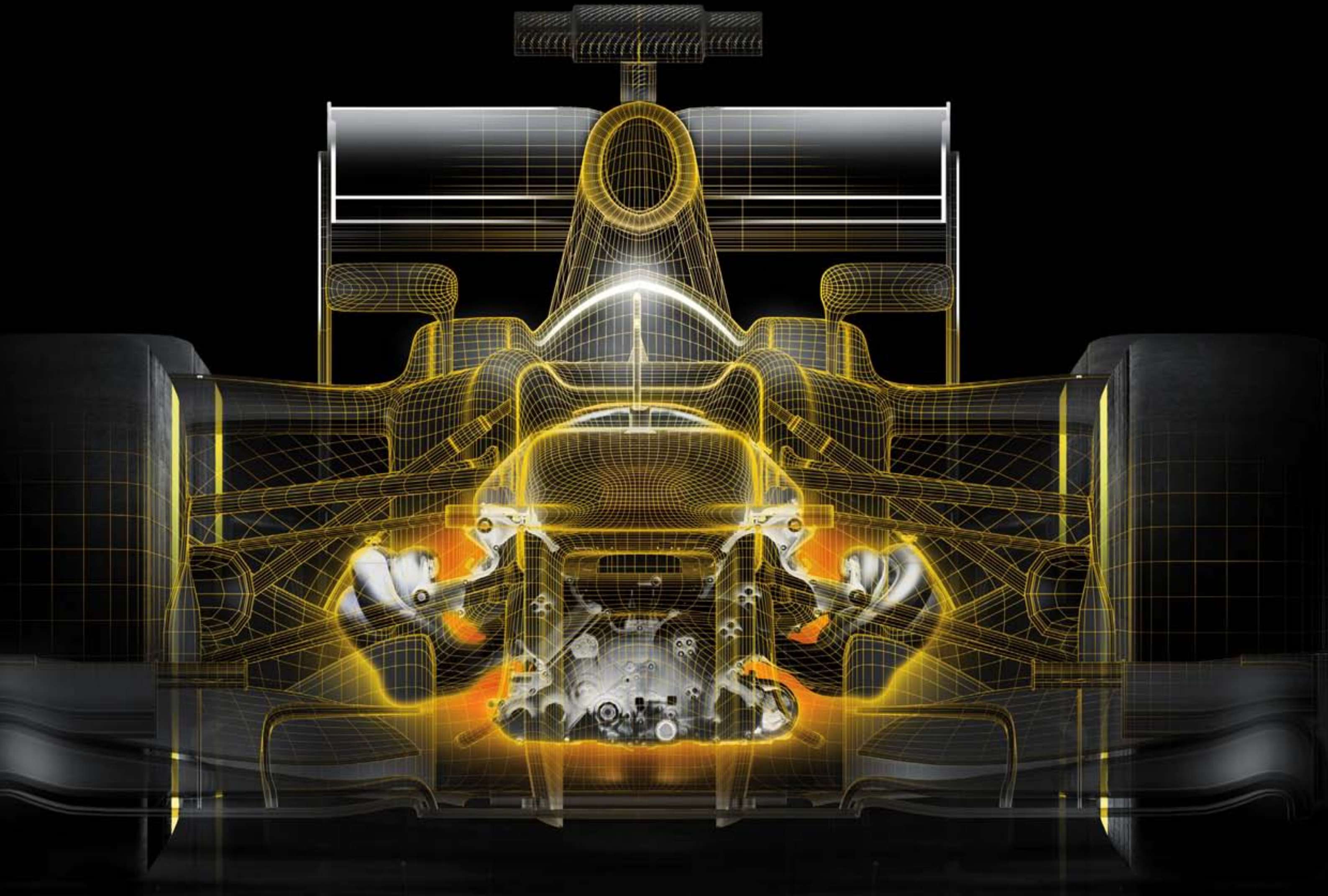
Renault RS27

Full details of the Formula 1 championship-winning V8



Genesis of the Red Bull • The V8 engines • Advanced CNC machining • How an F-duct works • Flexible wings • J dampers

The best of the V8s

Racecar Engineering takes a closer look at the headaches and triumphs that came of designing the most successful engine in modern F1 history

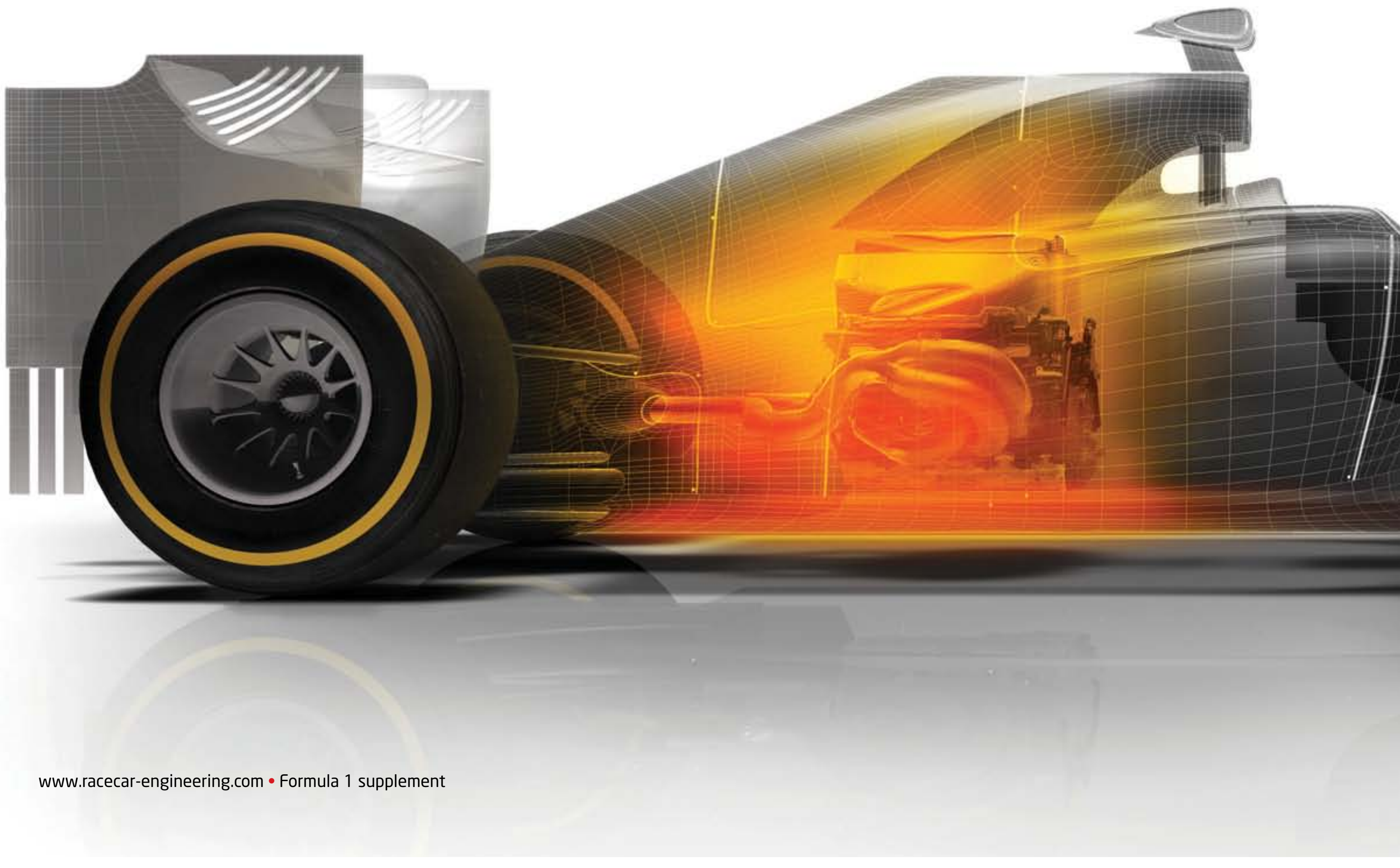
BY ANDREW COTTON

After eight seasons, Renault's RS27 is the most successful Formula 1 engine, winning four championship titles, and at the time of writing having won 58 races, as well as racking up 64 pole positions and 54 fastest laps. And with Sebastian Vettel having just claimed his fourth successive title, and with Red Bull, Lotus, Caterham and Williams all using the engine this year, those scores could increase still further at the last two races of the year.

The engine has been in circulation during some of the most demanding changes in Formula 1. When the engine was first conceived in 2004, the chase for ultimate revs was on, and the first engines were designed accordingly. From there, rev limits were reduced, first to 19,000rpm and then to 18,000rpm, and the specification of the engines was frozen.

Alongside those changes came the introduction of KERS and exhaust-blown diffusers, both of which changed the way in which the engine was being used. At the forefront of it all was the Renault RS27, assembled at Mecachrome in France.

The scale of the engine build is simply incredible. The company has built 1,271 engines, 683 for the track and 588 for the dyno. Between them, the engines have run more than two million kilometres and, despite the freeze in regulations, development has been taking place to produce reliable engines that have been adapted for a completely different world of Formula 1 compared to 2006.



'All of the systems and parts require a great deal of attention, care and maintenance,' says Rob White, deputy managing director, technical, at Renaultsport. 'However, the most difficult parts to maintain are always the perennially stressed parts, such as the pistons, connecting rods and bearings that the power travels through.

For example, the pistons are stressed to more than 8000 times the force of gravity (they accelerate from 1-100km/h in less than 1/2000th of a second). The actual weight of a piston is only 250g, but when the engine revs to its maximum limit of 18,000rpm – equivalent to 300 revs per second – the acceleration exerts a force of two tonnes on the piston and conrod.'

BEFORE THE RS27

It was on 6 October 2004 that the first official technical specification of the RS26 – the first Renault V8 – was distributed around the Viry-Chatillon offices. The objective was to design a V8 engine with a 90-degree angle as close as possible in specification to the RS25 V10, which respected the FIA's targets for mass, centre of gravity and crank centre line height. The objective was to use as many RS25 pieces as possible to minimise the risk of reliability and performance.

'The first V8 came from the last V10, and we designed it with the maximum technology of the V10 to help with reliability and not to imagine new things to make sure that all is OK at the first race,' says Léon Taillieu, project leader of the RS26. 'After that, we adapted all the parts to create the V8, but the general shape – like scavenging, oil circuit and water circuit – was all the same.'

Changing to the V8 meant that vibration was a problem, as was cylinder head reliability. 'The first thing was to look at the vibration, torsional vibration behaviour,' says Taillieu. 'We had to choose between two or three firing orders, so we made a lot of simulation around that and chose the best one for the reliability and the acoustic behaviour. The acoustics in a natural aspiration engine is major for the performance.

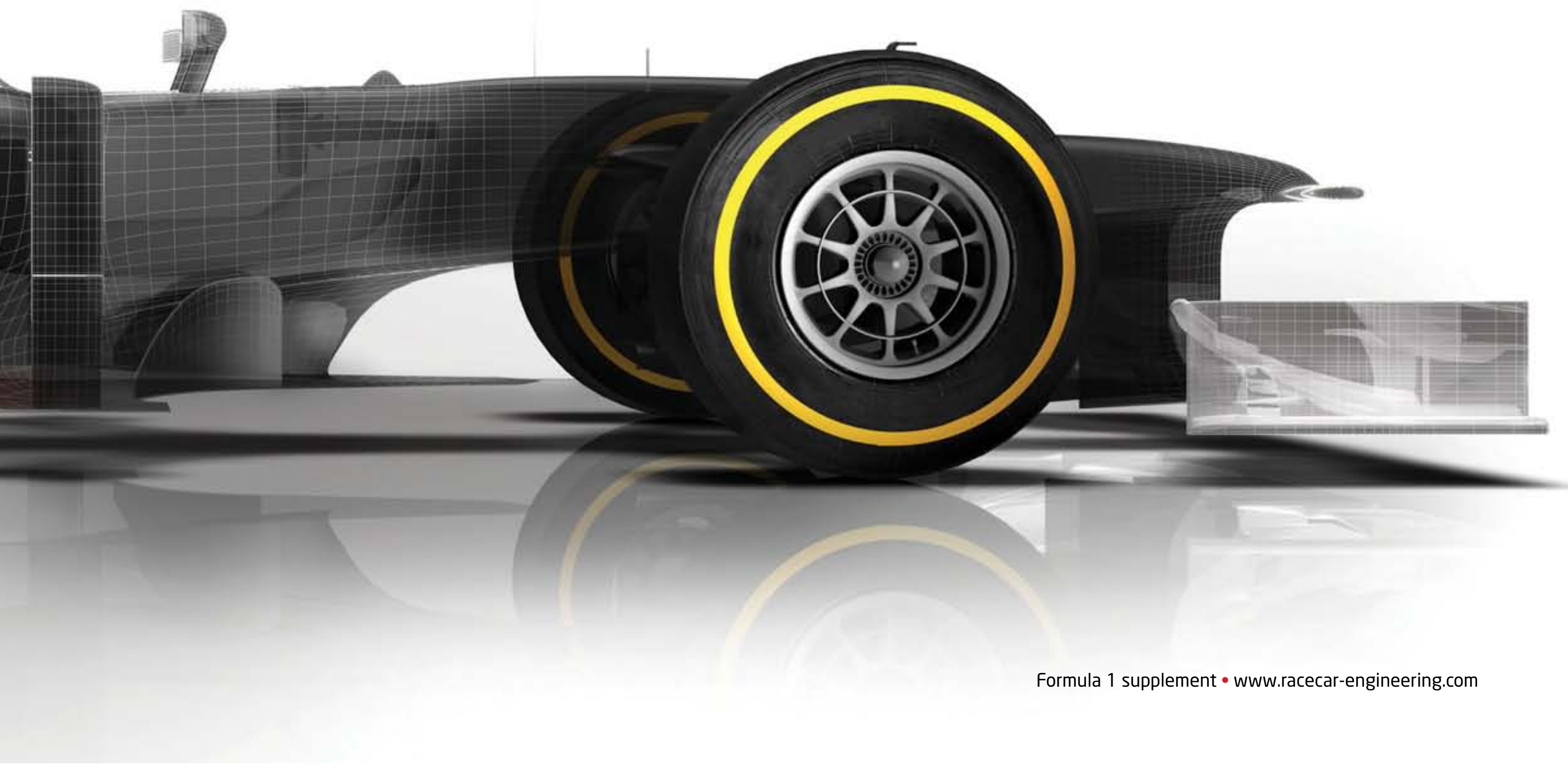
'At the time, the engine was not frozen. At the time, we had a lot of problem with pistons because we tried to increase the revs. We had cracks on the roof of the pistons, due to the load, which comes from the revs. The higher the revs, the more the load and the more big stress, and then you have cracks and break the piston. We had to redesign the pistons and change the materials. The number of references of piston was between 70-100, so there were a lot of iterations.'

In March 2006, the Renault F1 team won its first race of the season, with Fernando Alonso, while Giancarlo Fisichella followed that up with victory in Malaysia and Alonso again in Australia. For the San Marino Grand Prix in April, the team introduced the B spec of the RS26, with a new cylinder head, insulated ports, new camshafts and enhanced exhausts. Later that year, injection was increased to 100bar for the French Grand Prix. By the end of the year, five variations of the engine had been introduced, including low friction pistons, new valves, improvements to the oil system, conrods and camshafts. Power had increased from 680bhp to 700bhp.

For the 2007 season, the engines were fixed in specification, and changes were only allowed for issues of reliability. 'Midway through 2006, the atmosphere became very different,' says Axel Plasse, project leader for the RS27 engine. 'We had to face a very new challenge as we learned that the engine freeze was coming. It almost felt that all the work we had done should be thrown away as we would have to use the previous engine. This completely changed our mentality – I can remember writing to Rob White asking if we still had jobs! There was a point where we couldn't go backwards – we couldn't put the pieces we had developed back on to the shelf as they were bespoke. We managed to push a lot of the innovations through, but it was very close and the 2007 engine, which has been used for seven seasons since, came within a hair's-breadth of not being born.'

'At the beginning, we were very worried by the new regulations,' says Taillieu. 'However, we discovered that to limit the revs and development was interesting. The main focus was on friction between the parts. We did a lot of work on the coatings between the parts; we developed a carbon coating and the lubrication system, in order to reduce the oil flow. The more oil you put in the engine, the more difficult it is to scavenge the engine. If

The objective was to design a V8 engine with a 90-degree angle as close as possible in specification to the RS25 V10



After 12 constructors' titles, Renault returned to 'its core activity as an engine supplier' in 2011, supplying four teams with the RS27 during 2013

oil stays in the engine because you are not able to correctly scavenge the oil, you increase friction between the moving and static parts.

'We worked on the vibration and in all areas that we were able to work. If you change the oil, you reduce the friction between the parts, and therefore you reduce the reliability of the parts. They come into contact, and then you have to develop a specific coating to make the engine reliable again. When it is reliable again, you use this oil with even less friction, so you reduce the friction and increase the power!

'Our target was to have the engine at the minimum weight, 95kg, in order to give to the team the maximum opportunity with ballast so for our side for us to be at 95kg and minimum height of the centre of gravity. We are not able to go below this weight or centre of gravity by regulation. We had a small amount of ballast on the engine – less than a kilo – and we had a small possibility to change it from the back to the front of the engine, but it was not a big issue.

'It is more than 50bhp between the first V8 and the last one. The change from 2007 is between 30-40bhp.'

STANDARD ECU

The introduction of the standard McLaren ECU in 2008 again provided a lot of work for the engine department. The introduction automatically outlawed launch control, active engine braking and many other elaborate control algorithms. For the 2009 season, a new rule limited each driver to a maximum of eight engines per season. The engine had to be validated for life of approximately 2500km and the rev limit reduced to 18,000rpm. KERS was also introduced at the same time, which meant that the demand on the engines was different.

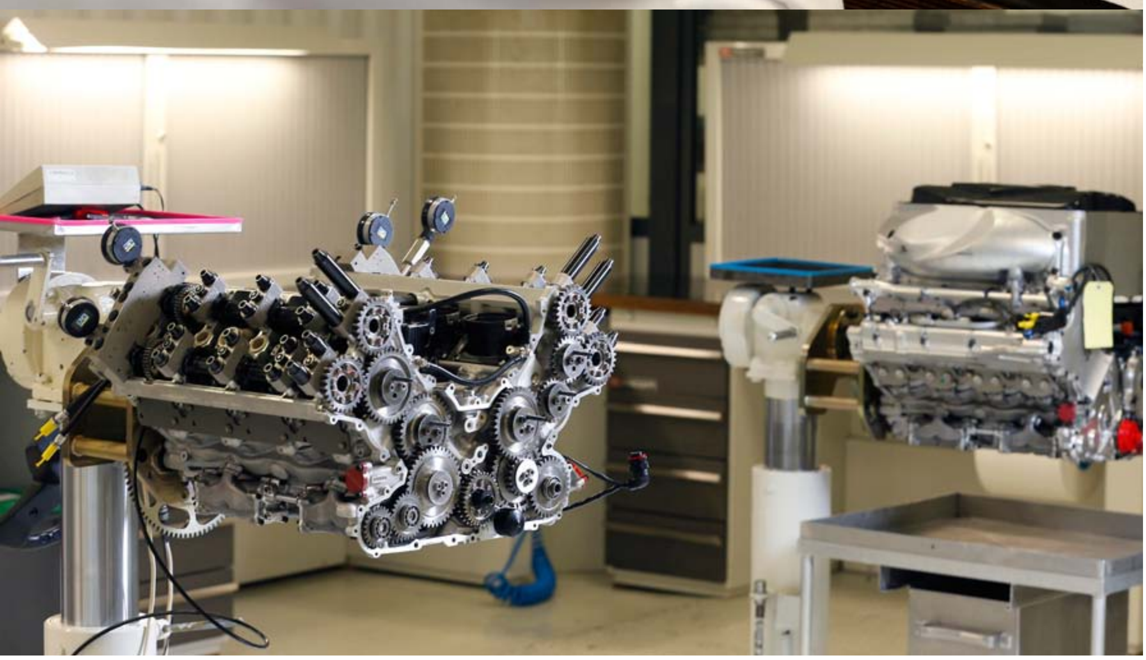
'When the FIA introduced the reduction in rpm in 2009, they opened Pandora's box,' says Plasse. 'We had a one-shot, intense opportunity to change the parts directly affecting the tuning of the engine – so the injectors, trumpets, inlet ports and everything to do with the inlet system. We changed a lot of the reference points and reworked a significant proportion of the engine. We have also seen an increase in engine life and a reduction in the number of engines per year.

Engineers at work on the soon-to-be-retired Renault V8 at the Mecachrome facility in Aubigny-sur-Nère, central France

'Normally, when you drop the rpm, you drop the bhp. It has traditionally been our credo to increase the rpm as a normally aspirated engine will generate power from rpm. For a given torque level, if you increase the rpm by 10 per cent you increase the power by 10 per cent.

'To reverse this process and reduce to 19,000rpm and then to 18,000rpm was a major sea change and we felt that we would really lose out. However,

'At the beginning, we were very worried by the new regulations'



Renault have continually made performance gains without increasing bhp, for instance through retuning, as well as working with partner Total to find improvements through fuels and lubricants

we have still managed to improve the horsepower and make the car go faster! This is partly due to the retuning at 18,000rpm, but also due to several other important ways we worked with the engine. We have also worked very closely with our fuel partner, Total, to jointly gain performance through fuels and lubricants. They have greatly helped us in improving fuel consumption and reducing friction – I would say we are now one to two per cent quicker, purely thanks to the improvements in fuel.

'There have also been performance improvements thanks to the way that the engine is installed into the car, including – but not limited to – the now-famous blown exhaust, engine operating temperatures and so on. This cycle of continuous development, particularly in the past three years, has contributed to the cars being more than one second quicker. Most of these improvements have been without any increase in bhp whatsoever.

'We have radically improved the fuel consumption, not just in the improvement of the fuels we use, but also in the strategy of how we consume fuel. We have got more sophisticated in how we use the engine, such as cutting cylinders in corners and reducing the amount of fuel used, plus using different engine modes at different points of the race. It is fair to say we are now six per cent more fuel efficient, and all without changing any parts. This gives a major advantage as six per cent of a total fuel load equates to around 10kg of fuel, or between a 0.2-0.4 sec gain per lap.

BLOWN DIFFUSERS

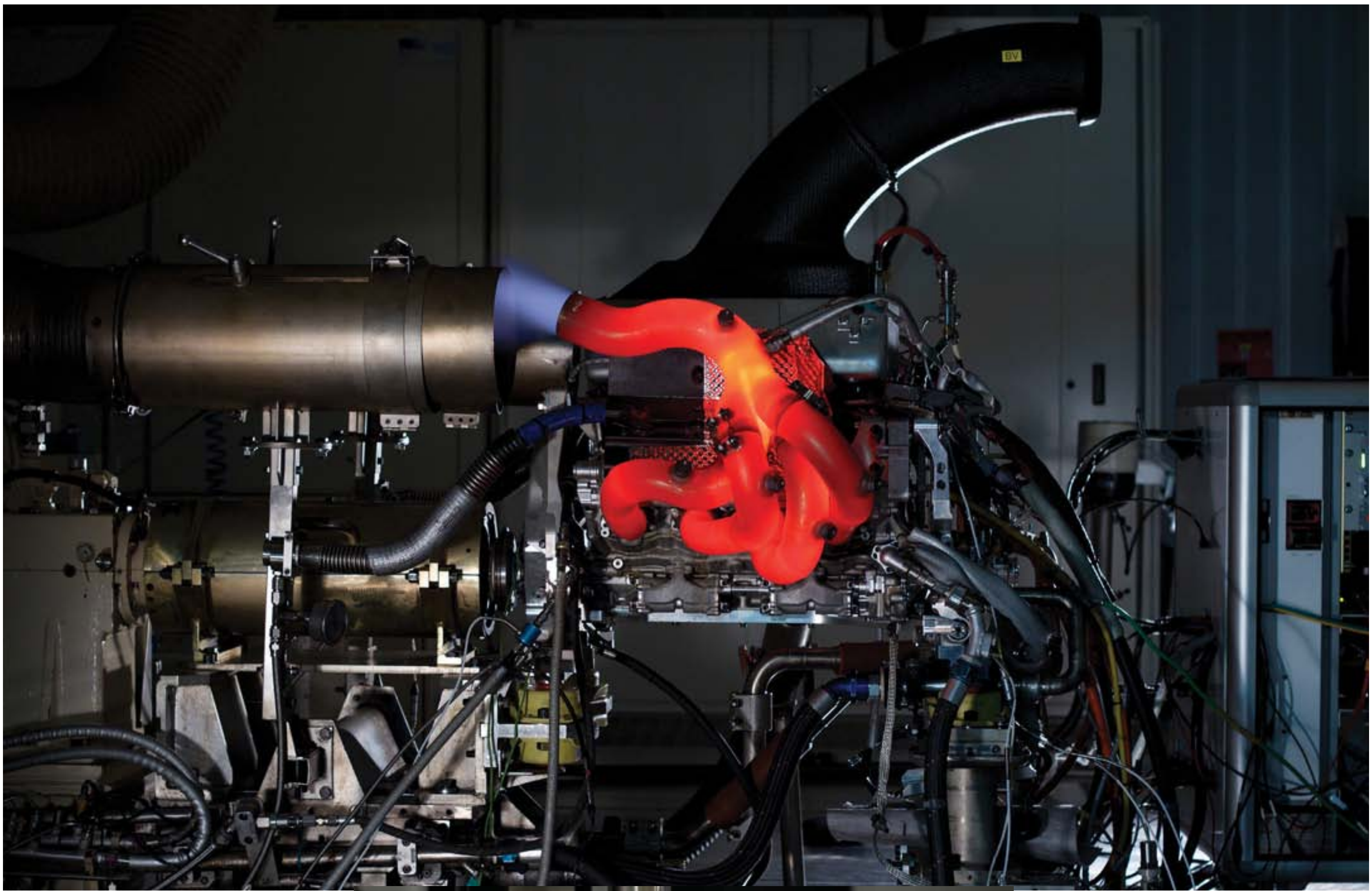
That all changed again in 2010, as by agreement KERS was not used, to keep costs in check. It was, however, a time when Renault started to experiment with exhaust blown diffusers.

'It is something that we had undertaken in a different world in a previous life and era, and so we had some parts that were turnkey and could be adapted to the V8 relatively easily,' says White. 'As we started to undertake exploratory work with our teams, it was clear that there was a performance vector to work upon that was in the system of references that was fixed engine spec. It was a given. Some of it came about from work that we were doing for reliability purposes. Initially, we reminded ourselves about this subject because some of the choices that we were driven to take for reliability purposes were – paradoxically – favourable for reliability in the measures taken to help our chassis colleagues to generate downforce.'

There were few changes to the hardware, although at the time there was a clear need for development. By 2011, almost every team was experimenting with some form of blown diffuser. Engine throttles were used to control exhaust mass flow and other techniques used to control engine torque delivery.

'When we change the pressure drop at the exhaust of the engine, you change the temperature of the piston,' says Taillieu. 'You increase the performance of the car through the blowing and map, but after that, the piston is not reliable and so you increase the performance of the car and the engine.'

With the location of the exhaust exits fixed for 2012, coanda exhausts were used to try to drive hot exhaust gas into the required area of the diffuser to maintain the downforce advantage, but the topic had



largely dissipated. The engine spec remained frozen, with only reliability open to change.

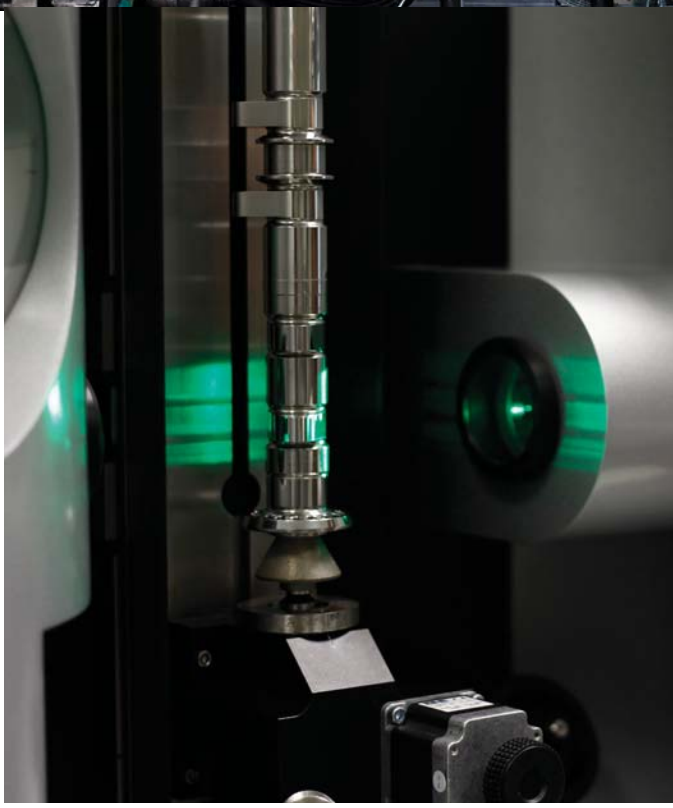
Driver torque maps became a hot topic as engine engineers sought to get the most out of the engine and its maps to improve overall handling. A clarification further restricting the scope of engine maps permitted was published mid-season.

While overt development has been outlawed for eight years, behind the scenes there has been a dramatic improvement to the RS27. 'We have largely corrected any outstanding issues and also reinforced some of the more fragile parts of the engine, such as the crankshaft, which has seen slight changes to its architecture and how we install it into the engine,' says Stephane Rodriguez, project leader for the RS27.

'We have also reinforced the conrods to stop breakages and to improve the dynamics of the system. However, the principal updates have been to the pistons, which are the most stressed parts of the engine. Due to the increase in engine life, these parts now have to sustain these enormous forces for a longer time, so through a redesign and recalculation we pushed through different designs and build in 2011 and 2012 to guard against reliability concerns.

'Another large area of development is to the oil system. We have spent a large time looking at reducing the dissipation across the engine and ensuring oil consumption is the same across all the engines. It is basic work to understand the different parameters and the impact on performance, but by doing this we can use less oil and therefore carry less weight, therefore achieving an overall lap time gain. Finally, in 2010 refuelling was outlawed, so we needed to work on fuel efficiency and how we use the engine at different points along the lap to improve overall race time.'

In the final year of competition, the spec was frozen and Renault had already turned its attention towards building the V6 hybrid for the 2014 season. Renault built a new dyno facility in Viry-Châtillon and in mid-October unveiled a new dyno at the Mecachrome facility where the engines are



Top: RS27 exhausts put through their paces on the Renault test bench
Above: running the rule over components at the Viry-Châtillon facility

'When the FIA introduced the reduction in rpm in 2009, they opened Pandora's box'

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Due to increased engine life, components have to sustain forces for longer

first run in before transport and final preparation takes place at the headquarters near Paris.

'Downspeeding the engine required us to make some changes, and at the time they were introduced there were some retuning opportunities permitted in the rules,' says White. 'Within the scope of the time available and the resources available we did the best possible job. We were pleased that we did not suffer significant performance drops with either of the reductions. These remain extremely high revving engines and operate over an extremely broad speed range, so everything to do with operating these engines over this speed range is extraordinarily difficult. We should never underestimate how good these engines are. The torque response is instantaneous, they run clean from less than 4000rpm to the red line, and the drivers get grumpy if the torque is delayed by a tenth of a second.

'Many people assume that the engines are similar since the specification has been frozen. However they are all very different as the specs were frozen at a point in time when the V8 was relatively immature. The technical regulations are strict and there are some common characteristics including the bore size and rpm limit, but there are many thousands of design decisions that are not fixed in the regulations.

'Perhaps it is not obvious but – in an unfrozen engine environment – there is more opportunity to converge on common solutions between the engine suppliers. The engine contribution to car performance is just as important now; even if frozen in performance, the impact on the car remains as important as it ever has been.'

THE OUTGOING ENGINE REGULATIONS AT A GLANCE

ENGINE BASICS

- Engines must be 4-stroke, 2.4-litre V8s, with a V-angle of 90 degrees.
- Crankshaft rotational speed must not exceed 18,000 rpm.
- Engines must be normally aspirated. Supercharging is forbidden.
- Minimum weight of 95kg.
- Engines must have two inlet valves and two exhaust valves per cylinder.
- Cylinder bore diameter must not exceed 98mm.
- Variable-geometry inlet systems or exhaust systems are not permitted, nor are variable valve timing and variable valve-lift systems.
- With the exception of electric fuel pumps, engine auxiliaries must be mechanically driven direct from the engine with a fixed speed ratio to the crankshaft.
- Only one fuel injector per cylinder is permitted; it must inject directly into the side or the top of the inlet port.

KERS AND ENERGY RECOVERY

- With the exception of one fully charged KERS, the total amount of recoverable energy stored on the car must not exceed 300kJ. Any which may be recovered at a rate greater than 2kW must not exceed 20kJ.
- The maximum power, in or out, of any KERS must not exceed 60kW; energy released from the KERS may not exceed 400kJ in any one lap.

TORQUE CONTROL

- The only means by which the driver may control the engine torque is via a single chassis mounted foot (accelerator) pedal.
- The accelerator pedal shaping map in the ECU may only be linked to the type of the tyres fitted to the car: one map for use with dry-weather tyres and one map for use with intermediate or wet-weather tyres.
- Engine control must not be influenced by clutch position, movement or operation.
- The idle speed control target may not exceed 5000rpm.

ENGINE USAGE (SPORTING)

- Unless he drives for more than one team, each driver may use no more than eight engines during a Championship season. The eight engines may be used at any race as required.
- Should a driver use more than eight engines he will drop 10 places on the starting grid at the first Event during which each additional engine is used. If two such additional engines are used during a single Event, the driver concerned will drop 10 grid places at that Event and at the following Event.
- If an engine is changed in accordance with Article 34.1 (after qualifying), the engine which was replaced may not be used during any future qualifying session or race with the exception of the last Event of the Championship.
- The engines are sealed and identified by the FIA, their installation in the car is declared and their use is followed by FIA technical staff. An engine is deemed to be used once the car's timing transponder shows that it has left the pit lane.
- Between Events, the engine exhaust flanges are sealed in so that the engines may not be started (or dyno tested).

ENGINE HOMOLOGATION (SPORTING)

- Under regulations introduced for the 2007 season, only homologated engines may be used in F1. The basis of the homologation is the specification of engines used during the 2006 Japanese Grand Prix.
- No fundamental changes have been made to the engine specification since this point and no modifications are permitted without the prior approval of the FIA following consultation with all engine suppliers.
- Performance-enhancing changes are not permitted. Changes are normally approved to facilitate engine installation in different cars, or for reasons of reliability or benign housekeeping.

TECH SPEC

Configuration: 2.4-litre V8

No of cylinders: 8

No of valves: 32

Displacement: 2400cc

Weight: 95kg

V angle: 90-degree

RPM: 18,000 (from 2009)

Fuel: Total

Oil: Total

Power output: >750bhp (typical car installation, typical temp/pressure/humidity)

Spark plugs: semi surface discharge

Ignition system: high energy inductive

Pistons: aluminium alloy

Engine block: aluminium alloy

Crankshaft: nitrided alloy steel with tungsten alloy counterweights

Connecting rods: titanium alloy

Throttle system: 8 butterflies

The rest of the V8s

With 87 victories between them – not to mention the odd failure – these engines had varied fortunes, but they all had something going for them…

Between 2006 – when the 2.4-litre V8 engine formula was introduced – and 2013, seven different engines were built and raced. The Renault RS26/RS27 was the most successful, but some of the other six are too often overlooked.

'If you put the four engines currently racing alongside each other and take them apart they are not the same,' says Rob White of Renaultsport F1. 'They don't behave the same way in the car and there is nothing in the current regulations that says they should do. It is wrong to assume that because each engine is of relatively stable spec that they are all the same.'

Ferrari 056

Teams: Ferrari, Toro Rosso, Spyker, Sauber, Force India
Wins: 45

Driveability was a key factor for Ferrari when it was defining the target characteristics for the 056, with the regulations requiring fixed inlet trumpets. Engine management was initially controlled by an integrated injection and ignition system from Magneti Marelli, which later had to be switched to the spec McLaren Electronics unit.

In 2007, some minor modifications were made to the engine. The combustion chamber was revised as were the valves, the inlet and the exhaust chambers – all aimed at optimising the torque curve, given the mandated limit of 19,000rpm. For the same reason, changes were made to the piston, the piston pin and the piston cooling jets to aim for the best possible reliability when running at the limit.

In 2009, the max RPM was further reduced, and the engine life increased. To cope with this, modifications were made to the inlet trumpets, the position of the injectors and the configuration of the exhausts.

Ferrari's V8 engine was a title winner and clearly a very capable unit. It is worth remembering that Sebastian Vettel won his first grand prix (Italy, 2008) in a Ferrari-powered Toro Rosso.

Mercedes-Benz FO108

Teams: McLaren, Mercedes, Force India
Wins: 40

Mercedes-Benz HPP in Brixworth have produced a long line of race-winning engines, and the FO108 was no exception. It is said to be very driveable in comparison to some other engines.

The Mercedes was to score three race wins with one single engine: in 2009, Jenson Button used FW049-01 to win races in Bahrain, Spain and Monaco. The unit went on to be used for Friday practice in Germany and Hungary, accumulating a total of 2016km.

It also scored two pole positions (Spain and Monaco) and spent 72 per cent of its racing laps in the lead, making it the most successful engine of the modern era – a statistic that Red Bull and Renault may dispute. In the same season, engine FW058-01 – used by Lewis Hamilton – also became the first hybrid-equipped powertrain in Formula 1 history to win a race, at the Hungarian Grand Prix.

Cosworth CA

Teams: Team Lotus/Lotus Racing, Marussia, HRT, Williams
Wins: 0

The Cosworth engine was believed to be the highest

Mercedes-Benz FO108


Ferrari 056

Cosworth CA

'Ferrari's V8 was a title winner and clearly a capable unit. Sebastian Vettel won his first Grand Prix in a Ferrari-powered car'

revving unit in Formula 1, and according to some it was at one point the most powerful.

The power developed by the CA was certainly more than respectable from the outset, climbing to in excess of 755bhp in its life, or 315bhp per litre. The latter specification Cosworth 3-litre 'TJ' V10 engines produced around 915bhp (or 305bhp per litre) for Red Bull during the 2005 season, reducing to 735bhp in restricted guise for Toro Rosso during the 2006 season.

The engine was mandatory for new teams joining Formula 1 in 2010, but saw its greatest success in the back of the Williams in 2006. A race win at Monaco came tantalisingly close, before the unit failed. For 2007, the teams switched to Toyota power, and then in 2012 to Renault

According to Williams engineers, the Cosworth unit was more limited in terms of mapping, and needed more cooling in comparison to the Renault. It also suffered from higher degradation over its engine life.

Honda RA806E

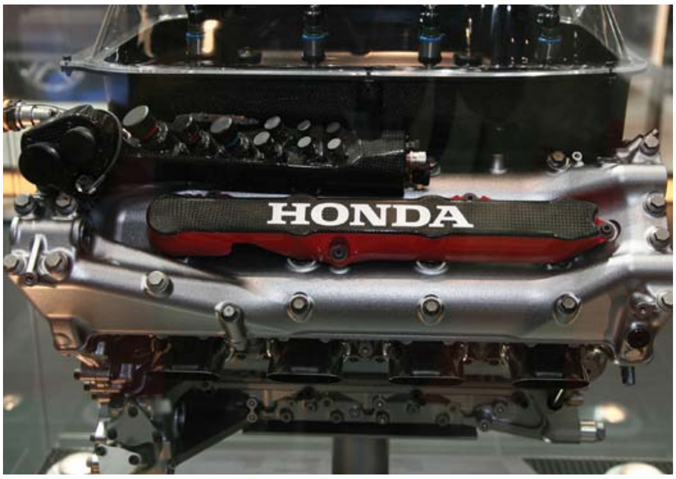
Teams: Honda, Super Aguri
Wins: 1

Honda's V8 engine won just one single race – Jenson Button in the 2006 Hungarian Grand Prix – though it could have won many more. Its reliability in the beginning of the V8 era was without doubt quite poor, meaning that during the first half of its debut season the units had to run at reduced revs. The engine had a relatively small bore and a long stroke. Despite the lower revs, there were seven engine failures in races during 2006 – the highest failure rate of the V8 era. 'We encountered seven engine failures in the course of 18 grand prix weekends, all of which were reciprocation-related problems,' explained one Honda engineer.

'Many of them were caused by the uneven quality of the parts affected by vibration in the crankshaft area. This had never been a problem with the V10. As a result we had to improve the quality control process. The long stroke increases piston speed and that makes durability harder to achieve.'

By 2009, the engine had received a number of updates, including a new induction system, fuel system, cylinder head and a new injector as well as modifications to the structure of the pneumatic valves to reduce friction. In addition to increasing peak power, the updates improved low- and mid-range torque.

Curiously, Honda R&D continued to develop the engine even after the company quit the sport at the end of the 2008 season. Honda never released its engine to customer teams – it was only fitted to the works cars and those of the satellite Super Aguri team.



Honda RA806E

Toyota RVX-V8

Teams: Toyota, Williams, Midland
Wins: 0

Toyota's RVX-V8 was thought to be the most reliable 2.4-litre V8, but this led some to claim that it was too conservative and that it was not as powerful as other units. After Toyota pulled out of F1 at the end of 2009, the engine was still available to customer teams. None took up the option.

BMW P86

Teams: BMW-Sauber
Wins: 1

BMW never sold its engine to customer teams. Few technical details were ever released, but in 2009 it was rumoured to produce 810bhp – which would make it the most powerful of the era (more power than the Cosworth CA). That season it was mated to super capacitor-based KERS. However, it never really delivered the expected results and was quietly dropped. BMW left the sport at the end of the season and Sauber promptly switched to Ferrari power.

Note: this supplement went to press shortly before the 2013 Brazilian Grand Prix weekend

Toyota RVX-V8

BMW P86


RENAULT
FXDD
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Keeping it in the family

Adrian Newey's recent Red Bulls have towered over the competition. We look back with him at this trail-blazing lineage of victorious V8s

BY SAM COLLINS

The 2.4-litre V8 era was generally a fairly open period which saw cars powered by BMW, Honda, Ferrari, Renault win races, while Toyota and Cosworth saw a number of podiums. But what will almost certainly be remembered will be the dominance of just one team – Red Bull Racing.

Red Bull Racing arrived in Formula 1 in 2005, buying the assets of the Jaguar team, including its staff and its Milton Keynes base. It had a fairly anonymous first season, but things started to change in 2006 when Adrian Newey joined Red Bull Technology, the company that develops the cars raced by Red Bull Racing, and which in the past has also looked after designs for Toro Rosso. Indeed the first win for a Red Bull car was at the 2008 Italian Grand Prix when the Toro Rosso STR3 (a Ferrari-engined variant of the Red Bull RB4) took the flag driven by a young German named Sebastian Vettel. It was the first win for a Newey-designed car since 2005. It would certainly not be the last.

In the last two decades, Newey's cars have won 10 World Constructors' Championships and 11 Drivers' titles. His philosophy is not one of aggressive revolutions in design, but rather gradual steps in a particular direction.

'The way I have always tried to work is that if you can get the concept right in the first place then within stable regulations I think it is good to evolve a car from there,' says Newey. 'That's what I did at Williams with the FW14 through to the FW16. That concept stopped at the end of 1994 when there was a big regulation change. As a result, the Williams FW17 was a brand new car that had nothing to do with the FW16 due to the rule changes. From then, the FW17 to FW19 were very much evolutions of each other. It was the same during my time at McLaren, the MP4/13, MP4/14 and MP4/15 were all very similar.'

Newey admits, however, that this approach has not always worked as it should. 'At the end of the MP4/15, I felt that while there was no big regulation change, the concept we were using had reached its limits,' he says. 'So we went a new way with the MP4/16 and MP4/17, but I didn't get the DNA quite right with those.

'Continuity is hugely important. Really, Red Bull Racing is a team that first raced in 2005, and in truth that was a Jaguar painted blue. Then it had a steep learning curve of developing the culture – there were quite a lot of new people joining, and some people from the Jaguar days choosing to leave. So it was a period of quite rapid change and that took time to settle down, and to develop a way of working – a culture and an ethos – to develop some of the bigger tools, be it developing the wind tunnel, developing simulation... things that you can't just go to Argos and buy.'

DEVELOPMENT CURVE

'It takes some time to develop all those from scratch, and to learn how to use them and how to work with them,' he adds. 'Once you get to that stage, continuity becomes very important. People have learned to work with each other and it's then making that an ever tighter-knit group and trying to maintain it as the team continues to grow. It's been flat for the last couple of years in numbers as a result of the RRA, which I think is very good. But it's an evolutionary thing which took us three or four years to settle down into.'

In 2009 a major regulation change was introduced to F1 – the aerodynamic packages of the cars were overhauled and given wider front wings and much narrower rear aerofoils. The bodywork was de-cluttered as the majority of winglets were outlawed. Slick tyres were re-introduced and hybrid powertrains would be allowed for the first time in the form of KERS.

Newey's response was the Red Bull RB5 (aka Toro Rosso STR4) – the first in a family line that would come to dominate Formula 1. 'The RB5 of 2009 was the first of a new line of cars with which we came up with the best solution we could find to the big aerodynamic regulation changes,' he says. 'That was really the biggest regulation change since flat bottoms came in back in 1983. We are always trying to maximise the downforce, have a reasonably broad operating window, get the weight distribution where you want it, have something that is structurally sound, and all with a light c of g. It's all the obvious points – there's no magic bullet in it. That big regulation change came at a good time for us, because it coincided with the point where we had started to gel together as a team.'

Sebastian Vettel in the Toro Rosso STR3 Ferrari at a damp Monza in 2008 – the first victory for a Red Bull car, and Adrian Newey's first win since 2005

The rear of the car featured pullrod-actuated dampers which hadn't been seen in F1 for some years, and the resulting compact and 'great' rear end is the reason why Vettel dubbed his RB7 – which also featured the concept – Kinky Kylie. Newey, however, takes something of a more reasoned view for the layout: 'the pullrod suspension at the rear helped to package some of the major components lower down, so the design was really a combination of c of g height and general packaging, which we felt suited the new regulations much better than the pushrod. It basically allows much tidier flow to the lower beam wing.'

That said, at first the concept ended up being something of a hindrance once it became clear that the loophole in regulations identified by Honda's Ross Brawn would not be closed. As a result, the Brawn BGP001, Williams FW31 and Toyota TF109 all featured so-called double deck diffusers, the Red

'The RB5 was the first of a new line of cars with which we came up with the best solutions to the big aero regulation changes'

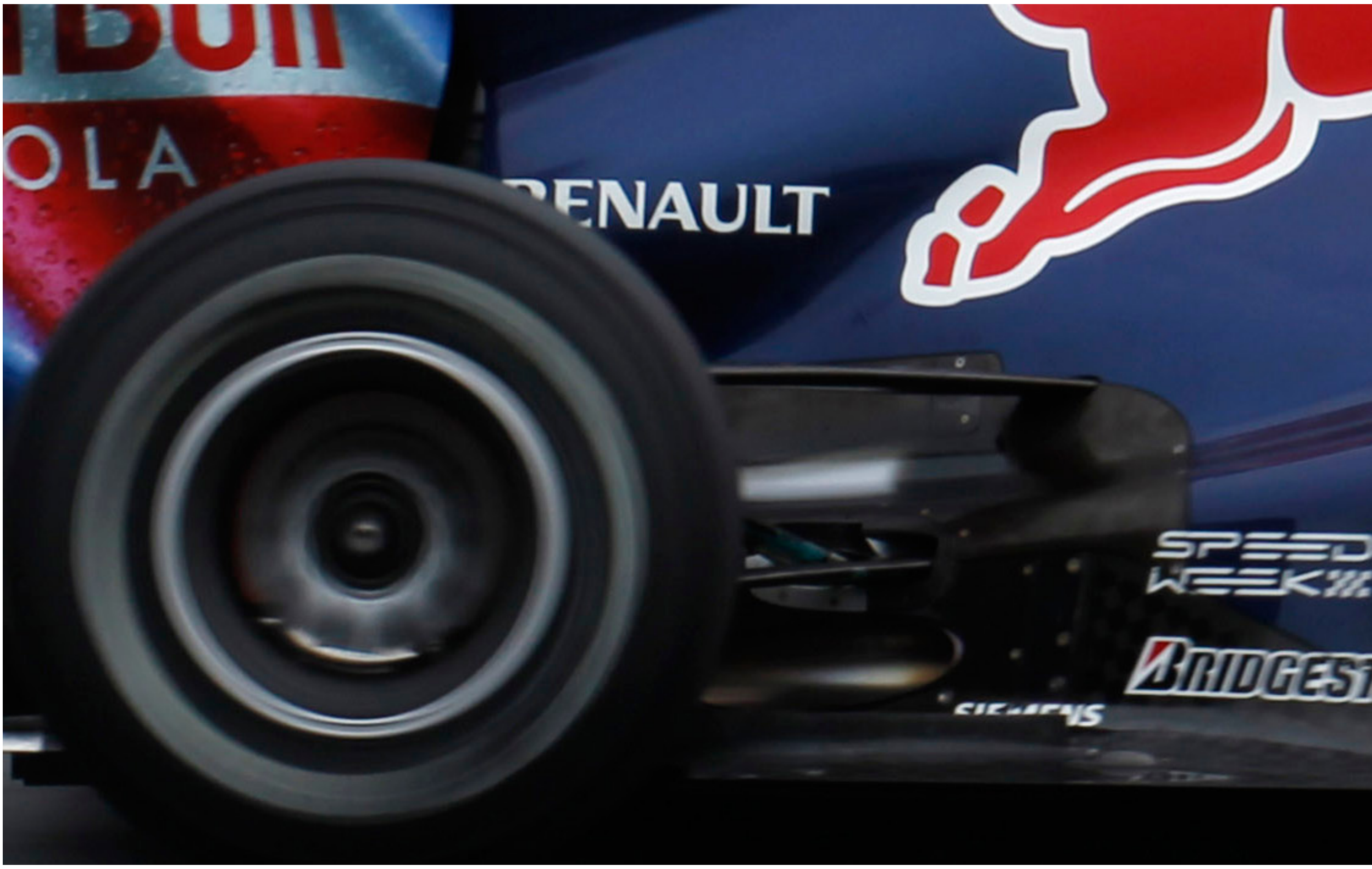
Bull RB5 did not and as a result it was left with a significant aerodynamic disadvantage.

'I think with a single diffuser car, pullrod suspension is a very elegant solution,' Newey says. 'But for a double diffuser, with the height that the diffuser then uses, it's much less clear cut. It compromised the RB5 a little bit by having to try and package a double diffuser on to a car that just wasn't designed for it. RB6, of course, was designed for the double diffuser, and then we debated whether to stay with the pullrod or not. I think we elected to, because by then we had some experience with it, and were happy with how it worked in general. But equally, had we spotted double diffusers earlier, we may have stayed with pushrod for RB5 and RB6. The whole thing with the double diffusers was not about the regulations. It was about Max Mosley's stand against the teams – especially Ferrari and McLaren – and we rather got caught in the crossfire.'

Once Red Bull caught up in the diffuser race, the RB5 became a force to be reckoned with – winning six races. Its successor, the RB6, however, was built with the double diffuser in mind. It also introduced another technology

LAT

The Red Bull RB5 – which gained six wins and five poles in 17 races – was the first in a design lineage which has gone on to dominate F1



LAT

Red Bull Racing experimented with exhaust layout throughout the car, and attempted to hide its work with stickers. They were effective for about 24 hours…

which would come to dominate F1 aerodynamics, the blown diffuser. It also had to accommodate a much larger fuel tank as in-race refuelling was banned.

'The RB6 is an evolution of the RB5,' said Newey at the car's launch. 'We tried to look at what bits we could improve, but it was more a case of looking at the fuel tank and the diffuser. Last year we took the decision that we were going to fit a double diffuser to the RB5 and not change the gearbox, because we didn't have the time or the resource to do that.

'Obviously for the RB6 we designed the gearbox and rear suspension to have that from the outset. And like other people we were able to fit a somewhat larger diffuser than we were able to in 2009. We stuck with the pullrod rear suspension – having been on it for a year and started to understand its strengths and weaknesses, so we felt it was the right way to continue.'

But in hindsight, Newey feels that despite being a good design, the RB6 may actually have been the weakest car of the family line.

'The 2010 car was the first year where we designed it from the outset to have a double diffuser,' he says. 'We got a lot out of that concept and we were quite aggressive with the packaging of the car. It had a very long gearbox to maximise the area of the double diffuser. Performance-wise we have always had our nose ahead with this family of cars, and that's certainly true of the 2010 car. But we struggled with a lot of reliability issues both on our side and also on the engine side. There were a lot of points thrown away as a result of that, and to be honest quite a few errors along the way.

'We made much harder work of the 2010 championships than we should have done. While we wrapped up the constructors' championship with a race to go, the drivers' went right down to the wire. Indeed, if the second Renault driver (Vitaly Petrov) had not managed to keep Fernando Alonso behind him, we would not have taken the title.'

'With the 2010 car we struggled with a lot of reliability issues, and there were quite a lot of points thrown away as a result of that'

BEST OF THE BUNCH

There is little doubt, however, as to which car Newey thinks was the strongest of the line in terms of relative performance. 'With hindsight it is clear to see that the 2011 championship was the easiest one,' he says. 'We had a car that we were just able to always extract a bit more performance from and that let us keep our nose ahead all season.'

The RB6 was described by driver Mark Webber as being 'like you are driving a limousine' due to its extra size and weight – a result of the larger fuel cell.

'We initially concentrated on the challenges of almost doubling the size of the fuel tank from the no refuelling regulation and what impact the narrower front tyre would have,' says Newey. 'The 2010 aerodynamic work started around June 2009, looking at the monocoque where there was a small regulation change to the V-section chassis we used. The rest of the chassis work was aerodynamic optimisation and accommodating the extra 70-odd kilos of fuel.'

As was the case with the RB5 and all of the later cars, Newey and his team had to accommodate two very different drivers – the 64kg of Sebastian Vettel who is 174cm tall and the larger 75kg frame of Mark Webber, who stands at 184cm. 'The car has to be designed around Mark, which means that the cockpit has to be a bit longer than the minimum regulation and the fuel tank has to be moved rearwards slightly because fuel is not allowed to be stored ahead of the driver's back,' says Newey.

'Once we've done that, fitting the shorter driver in, Sebastian, is relatively easy. With Mark we have a driver who's on the heavier end compared to Sebastian. That

Apart from a system to reduce the disruption to airflow in the diffuser caused by the rear wheels, the RB8 was a relatively straightforward evolution to the RB7

means he has less freedom on weight distribution. The obvious solution to that would be that drivers have to carry ballast on the side of their seat, but that's something that has been discussed and hasn't happened so far. It really means that if you make the wrong move, you're locked into it for a while. It's one less variable, but it's the same for everyone.'

The Red Bull RB6 was the first modern F1 car to be fitted with a blown diffuser. Designed to use the exhaust gases to seal the diffuser off from turbulent flows from the base of the rotating rear wheel, the concept first appeared in pre-season testing.

Red Bull was keenly aware that as soon as other engineers realised that the exhausts had been repositioned, they would soon be on to the concept, so it tried to camouflage the layout in a fascinating way. Stickers with the image of exhaust exits were placed on the rear bodywork of the RB6 exactly where the exhausts used to be positioned. But the real exits had been moved to the now familiar position on the floor of the car.

The deception worked for 24 hours – it was one of the first demonstrations of the power of the internet in F1 with thousands of pairs of eyes studying each car for upgrades. Just a few years earlier the deception would have worked for months.

That head-start in exhaust technology would give Red Bull a clear advantage in 2011. With 11 pole positions, six wins and 383 points from 11 races it is fair to say that the RB7 dominated the first half of the 2011 F1 season.

Due to a regulation introduced for 2011 along with a new tyre supplier, Pirelli, weight distribution was something less of a headache for Newey and his team for the RB7. The weight distribution of all 2011 cars was fixed at no less than 291kg on the front axle and 342kg on the rear, and with the 640kg minimum weight, teams only had a 7kg window to work with. Other design limitations – such as the c of g height for the engine – also further reduced some of the design choices available.

But the big change in the rules went directly in Red Bull and Newey's favour – a ban on double diffusers. This allowed the team to finally reap the full benefit of its pullrod rear suspension. It will likely be said in years to come that the FIA didn't quite get the under-body aerodynamic regulations right, as double diffusers gave way to the even more controversial 'hot blown floors', where cars would use 100 per cent throttle 100 per cent of the time with the driver's right pedal becoming little more than a torque demand switch. Most radically, this idea was exploited by the Renault team with the front exhaust exits seen on the R31.

MORE KERS THAN BLESSING?

'I think some people were saying that they were hot blowing the floors to balance their KERS out, which seems rather against the whole principle of it,' says Newey. 'KERS is meant to be a fuel-saving strategy, so to claim that you burn excess fuel and blow the floor in order to offset the influence of the KERS and achieve a neutral brake balance seems rather against the whole intent of green technology. The way we were using the exhaust, the effect on KERS would be very small.'

The RB7 was the first Red Bull to fully exploit KERS to any great note. It did not use the fuel tank volume in the monocoque to accommodate the batteries. This was a major change in concept to the RB5, which was the first Red Bull designed to take KERS. 'On that car it was in the fuel tank, so the RB7 was kind of in-between RB5 and RB6 in chassis terms,' says Newey.

'When we freed up the volume for fuel between RB5 and RB6, we also changed the shape of the monocoque alongside the fuel cell at the same time. Inevitably, there's always a fight between radiator packaging and fuel volume as they are fighting for the same volume.'

The re-introduction of KERS joined DRS as headline changes for the 2011 season, but one of the critical issues for the teams was the arrival of Pirelli as the sole tyre supplier to F1. With the RB7 proving to be the fastest car in qualifying and winning the most races, it could be said that Red Bull got the best out of them, but Newey is not so sure. 'Ferrari seemed to be pretty kind on their tyres, arguably kinder than us,' he says. 'It's not as simple as having a good tyre model, then you understand the tyre. That might allow you to understand it, but it won't necessarily mean you can get good performance. In truth, I think our pace was down to the

Red Bull camouflaged the new layout during testing by placing stickers of exhaust exits on the rear bodywork, where they used to be

WRI2

The RB7 rear wings and suspension during an early view of the all-conquering car at testing, Circuit de Catalunya, Spain in 2011

overall car. I like to think that if we were on Bridgestones, our performance relative to the others would be probably fairly similar to where we were on Pirellis. In other words, I don't think that the change from Bridgestone to Pirelli particularly caused a change in the competitive order.'

In 2012, however, the Pirelli tyres were a dominant factor and did indeed cause a change in the competitive order, with Williams winning its first race for many years as a result. The resurgence of the Honda/Brawn team – now in the guise of Mercedes – also made Newey's job harder. On top of this, off-throttle blowing was banned – Renault had admitted that it increased fuel consumption by up to 10 per cent at a time when the sport's environmental credibility was under stiff scrutiny.

'It was a difficult task to stay where we were,' says Newey. 'We lost the exhaust technology with the restriction on exhaust outlet position, that we'd otherwise have perhaps been ahead of the pack with in the last couple of years. That led to a big rethink over the winter. We designed the RB7 around that exhaust position, and were probably the only people to do so other than Lotus.

'Regulation restrictions – like the lost exhaust – are a bit frustrating, because they are precisely that: restrictions. They're not presenting new opportunities or revenues particularly, they're just closing doors. I enjoy regulation changes, but I always rather lament regulation restrictions.

'As a result of those restrictions we had to go back and look at how we developed the car. Probably one of the key things there was the rear ride height. The exhaust allowed us to run a high rear ride height, but it was much more difficult without it to sustain a high rear height, so we had to go back down and redevelop the car around that lower ride height.

'With the RB8 it was about damage limitation from the cut in downforce in losing that exhaust technology. We have certainly suffered more than our competitors in terms of the exhausts. We were the first to do it in 2010, so we were on that track for two years and had probably taken it further than other people. It was difficult to get the car to work properly with it missing – we really had to go back and re-learn the baseline.'

EXHAUST AVENUE

The RB8 was launched with a fairly conventional solution, but after initial testing, it was fitted with a Sauber-style solution, which differs from the Coanda layout but achieves the same goal, reducing the disruption to air flow in the diffuser caused by the rear wheels.

'It was a combination of two things that hit at one time,' says Newey. 'One was the restriction on where we could physically put the exhaust exits, and the other was the restriction on the mapping of the engine. Those combined hugely reduced the exhaust effect, but did not reduce it to zero. Compared to the other teams, there are obviously two ways of skinning the cat in terms of getting the most out of the exhaust given the limitations in the regulations. The concepts used were different in the philosophy and the way in which they achieve the effect.'

Despite the change, the RB8 was still just an evolution of the RB7, and a continuation of the family line. 'Generally speaking, if a car is an evolution – which the RB8 was– it's kind of a gradual process,' says Newey. 'The knowledge from the development of the RB7 was constantly fed into RB8. You have to get the big bits out of the way, though, to hit the timescales, and the longest lead items on the RB8 were the chassis and gear case as well as the internals. The initial research centred on what was needed for those long-lead time items and it then progressed on from there.'

'Regulation restrictions don't present new opportunies – they close doors. I enjoy regulation changes, but I rather lament restrictions'

WRI2

The Renault RS27 V8, which powered the Red Bull RB7 to an impressive 12 wins from 19 races during the 2011 season

Red Bull supplied one of those long-lead time items – its transmission – to a customer team, Caterham. On the RB8 the layout is little changed from the RB7 and the unit found in the CT-01 and CT-03 (The Lotus T128 used the RB5 gearbox). 'With the gearbox, everybody now has instant shift, which means that you're engaging the new gear before you come out of the old gear, and you're using the backlash to get out of the original gear before you have the two gears fighting against each other,' says Newey.

'After that it is just reliability and packaging. On the RB8 the gearbox internals were the same as on the RB7, and quite a few of the assemblies carried over too. Wheel bearings, pedals and that sort of thing were all the same, so we only changed parts where there was a reason to do so. Between RB8 and RB9 there was virtually nothing new about the transmission. The internals are as near-as-damn-it identical, although the casing was slightly different. The changes there were very small. In 2012 we introduced a very high wishbone with the driveshaft passing through the middle of it which brought an aerodynamic benefit – and that's been widely copied by others in 2013. That was quite a decent step, but it's the usual problem in Formula 1… everyone sees it and copies it.'

It is worth noting here that the RB8 pushed the regulation hard in a couple of areas, resulting in two high-profile issues with the FIA. First the team was forced to change the design of the rear floor of the car. A new floor used at the Spanish Grand Prix and the Monaco Grand Prix featured a small cutout ahead of the rear wheel, but this was questioned by rival teams who argued that it did not conform with the technical regulations.

These state: 'All parts lying on the reference and step planes, in addition to the transition between the two planes, must produce uniform, solid, hard, continuous, rigid (no degree

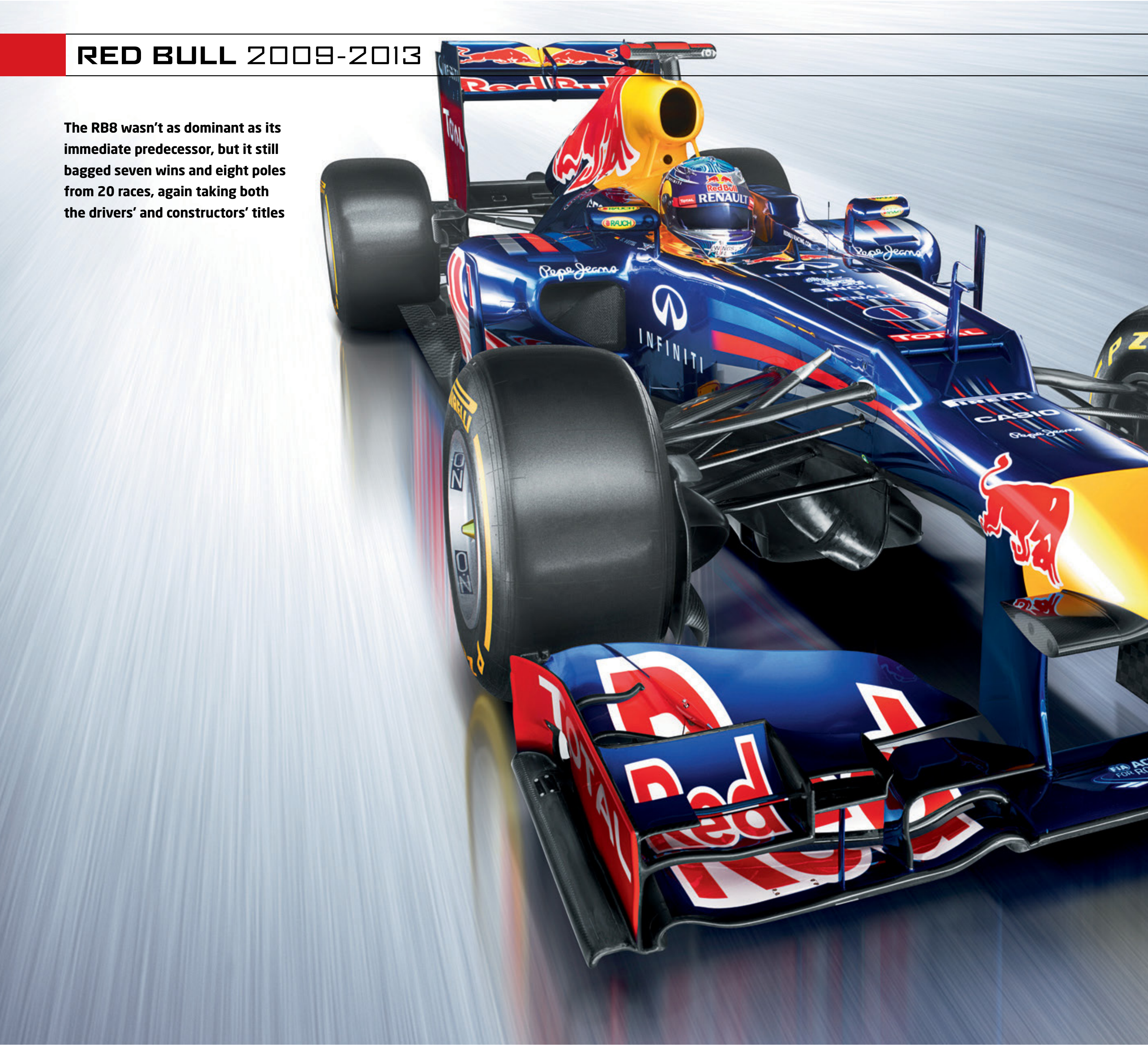
BLOWING THE NUTS

Early in the 2013 season, the RB9 tested with an interesting wheel nut layout – there was a hole in the centre of the nut passing right though the hub. These became cheekily known as 'blown nuts' and were also trialled by the Williams team. At the time their purpose was not disclosed, though some speculated that they were for brake cooling.

'Last year we had a duct through the wheel which gave some small aerodynamic gains,' Adrian Newey explains. 'It was trying to do what we had when we had the wheel covers in the past. The way we did it last year was declared illegal during the season, at Montreal. The solution that ourselves and Williams then experimented with at the start of this year was much the same thing, but done in a way that was legal.

'Overall, however, we did not find a big benefit to doing it.'

WRI2



The RB8 wasn't as dominant as its immediate predecessor, but it still bagged seven wins and eight poles from 20 races, again taking both the drivers' and constructors' titles

of freedom in relation to the body/chassis unit), impervious surfaces under all circumstances. Forward of a line 450mm forward of the rear face of the cockpit entry template, fully enclosed holes are permitted in the surfaces lying on the reference and step planes provided no part of the car is visible through them when viewed from directly below.'

To circumvent this, other teams – such as Ferrari – used a tiny slit between the hole and the outer edge of the floor, meaning that the hole is not 'fully enclosed'. The FIA technical department said that in its opinion the floor did not meet the rules as it interpreted them, and for the next race in Canada, Red Bull changed the design.

Another run-in with the FIA technical department took place at the German Grand Prix. This time it centred on the torque map loaded on to the car's McLaren ECU. The FIA's technical delegate, Jo Bauer, discovered the code ahead of the German Grand Prix and issued the following statement: 'Having examined the engine base torque map, it became apparent that the maximum torque output of both engines is significantly less in the mid-RPM range than previously seen at other events. In my opinion this is therefore in breach of the technical regulations as the engines… Furthermore, this new torque map will artificially alter the aerodynamic characteristics of both cars which is also in contravention of technical directives.' The mid-range torque map is critical in optimising the car's exhaust gas flow to get a blown diffuser effect, though it was not clear that this was what Red Bull was doing. Nonetheless, Bauer referred the matter to the event stewards.

Three hours after Bauer's report was released, the FIA stewards of the meeting announced that no further action would be taken. Their statement read: 'The stewards received a report from the FIA technical delegate, along with specific ECU data from Red Bull Racing Cars 1 and 2.

'The stewards met with the team representatives and the representative of the engine supplier Renault. While the stewards do not accept all the arguments of the team, they however conclude that as the regulation is written, the map presented does not breach the

'We'd think we had a handle on the 2012 tyres, but then something would happen to make us realise we hadn't properly understood them'

text of the Formula 1 technical regulations and therefore decided to take no action.'

Drivers of rival teams felt that the RB8 had more downforce, but transmitting that downforce to the track was just as important in 2012. Indeed, one of the biggest talking points of the 2012 season was the tyres, the impact of which Newey felt has been somewhat overplayed.

'Everybody talks like the tyres have become so much more critical in 2012 compared to the previous year,' he says. 'I think they were trickier to use generally, but equally the grid closed up again and that was partly due to regulations being restrictive and 2012 being the fourth season since those regulations were introduced. The cars were converging and the grid was getting tighter.

'So, if you are a tenth or two tenths a second slower, it might be a few grid places dropped, whereas the previous year it might have made no difference at all. It all put tyres into a bigger focus and quite often when you get these big swings between grid results between the teams, tyres are singled out as being the reason.

'But that's a bit too simplified in truth. Some cars will be better in high speed corners and not so good in low speed corners. Some cars may be better on bumpy circuits, but tyres are the visible feature that people just latch on to.'

Despite this, Newey admits that the 2012 Pirelli tyres were more challenging than expected. 'The tyres were very difficult to understand,' he said. 'Sometimes we thought we had got a handle on them, but then something would happen that made us realise that we've not properly understood them.

REVERSE ENGINEERING

'Effectively we were trying to reverse engineer someone else's product, so it was and still is tricky – and this is the same for all of the teams. Inside our own team we did not highlight anyone purely as a tyre specialist. But it's fair to say that we dedicated more time among our engineers than we would have done previously, or we would have done with a Bridgestone or a Michelin.

'If you compare them to – say – the height of the tyre war between Michelin and Bridgestone, then you got to the point where the race was really a series of qualifying laps and the drivers would therefore push very hard throughout without worrying too much about degradation, be it thermal or wear. That's different now. I think that brings a different set of skills to the floor, almost like Prost in the 80s, when he got the reputation for being The Professor, thinking about how he did the race. I think

KERS: RED BULL'S ACHILLES HEEL

If the Red Bull RB5-RB9 family line does have an Achilles' heel, it must be its energy recovery systems, as team radio transmissions during races regularly reveal system failures – something that by 2013 was almost unique to the team.

'At the root of the problem is the fact that we tried to develop the KERS package ourselves,' says Adrian Newey. 'It's based on the Magneti Marelli system that Renault used in 2009 and which we briefly tested on the RB5 pre-season before electing not to race it. Since then, everybody has gone off in different directions with that system as a basis, including ourselves.

'Developing KERS just isn't our strength. We are mechanical engineers, aerodynamicists and vehicle dynamicists – not KERS specialists. Part of the problem is that we have chosen quite aggressive packaging, putting the batteries alongside the bell-housing at the back of the car, which we've felt was good for the overall package of the car. Everybody else now has the batteries at the base of the fuel tank.

'From a packaging point of view, we felt that ours was a better route. We knew there would be heat issues with our placement of the batteries as it is a fairly hostile environment, and heat management has been a little bit of a problem. But most of the other problems have been – I think more than anything – simply our lack of experience in that area.'

This is one of the key areas in the design of the RB6-9. Placing the lithium chemistry cells – thought to be supplied by SAFT – at the rear means the car has some significant differences to its rivals. The team's package is still largely based on the Magneti Marelli system which first appeared in 2009, with some components similar or identical to those used by Ferrari. The unraced Peugeot 908 Hybrid4 LMP1 is also thought to share some components with this system.

TRICK MISSED

'In hindsight we missed a trick by not properly developing KERS in 2009,' admits Newey. 'The potential was always there, but in 2009 we were not mature enough as a team to take on that challenge. You could argue that between then and now in 2013 we have gained 0.4 secs from KERS. The rest has been the usual aero developments.

'It's fair to say that we always struggled at high track temperatures. Having the batteries where they are brings weight distribution benefits in terms of the car overall as we have shifted that mass rearwards – but thermally it is not where you would choose to put them.'

THE ANACHRONISTIC ADRIAN NEWEY

While every other car on the grid between 2009 and 2013 started out with a click of a CAD screen, the Red Bulls all started life as a hand-drawn design on a piece of paper in Adrian Newey's office in Milton Keynes, England.

'Whether you use a CAD system or a drawing board, ultimately it's a way of taking thoughts from in your head, putting them into a medium, developing them in that medium and then communicating it with others,' explains Newey. 'It's almost like a language, and what system you use is personal preference. But it is fair to say we couldn't realistically cope with many people in the company using drawing boards!

'Once I've done my paper drawings, they then have to be scanned, and then there's a team of two or three people that have to take those drawings and turn them into solid surface models. Nowadays, a drawing itself is of no use to anybody. Whether you're evaluating it in CFD or in a wind tunnel, the manufacturing is in the electronic world. The wind tunnel model and the manufacturing use computer-controlled machinery. The team have got used to me now.'

While Newey still relies on paper and French curves, the rest of his engineers use advanced digital tools to develop concepts. The team has a partnership with Siemens, and uses its NX software. It also utilises Teamcenter PLM to ensure accuracy and consistency of models and bills of material. 'It's the system that the guys here all felt comfortable using,' adds Newey. 'We benchmarked various systems in terms of overall performance and flexibility and how we wanted to use it, and found that it was the one most suited to us.'

Newey's design methodology is primarily aerodynamic, something most teams now imitate. 'It's the way I've always operated, pretty much from the start of my career,' he says. 'I graduated as an aeronautical engineer, which means not simply aerodynamics. Aerodynamics was one of the subjects that one takes on the course, but so are structures, controls and so on. It seemed quite apparent to me that aerodynamics – from the very late-70s or early-80s – was becoming the major performance differentiator between the cars. So it makes sense for the aerodynamic side to lead the overall design of the car in terms of packaging. All the cars that I've been in charge of, dating back to the IndyCars of the mid-80s, have been designed to that ethos.'

This does not mean that aerodynamics always take priority, of course. Newey takes a pragmatic view to handling the engineering trade-offs. 'We have sufficient research and simulation tools that we should be able to answer questions. So for instance, if there's a compromise to be made between weight or stiffness – which are the usual things – then we should be able to input numbers and let them speak for themselves.'

But Newey is perhaps of the old school of racecar designers, as he loathes the level of restrictions found in the F1 technical regulations – so much so that he has more than once considered a career change to the world of the Americas Cup.

'I rather lament it. All of those changes of the concept from RB5 to RB9 are always due to regulation restrictions. Ultimately if the regulations become tighter and tighter then you end up with F1 becoming GP1. All the cars will converge to become more or less the same and I think that would be a great shame for the sport. For me, what differentiates F1 from tennis or golf is the fact that it is a combination of man and machine, and to win either the drivers' or constructors' titles you need a combination of good driver and good car.

'If the regulations mean that the cars are all more of less the same, it would reduce the attraction of the sport.'

that's coming back, which gives some variety and change in the field both race-to-race, during the race and qualifying to race. I think that's all good for the sport – certainly good for spectating.'

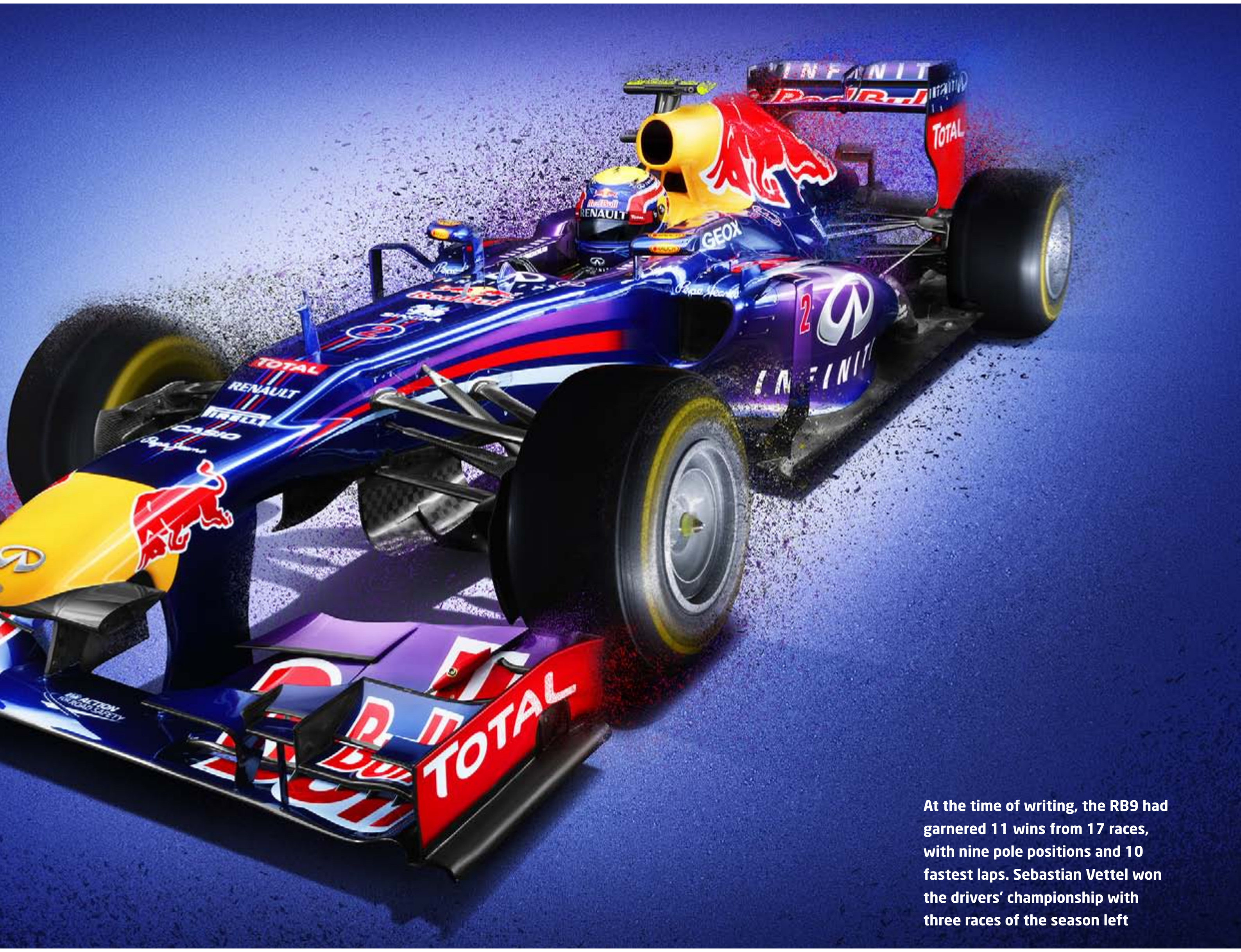
The RB8 was followed up by the RB9 – a car that courted no less controversy and just as many admiring glances from rivals. It was once again an evolution of the previous year's cars but featured some interesting details. At some point in the family line, interlinked suspension was introduced. Unlike some cars with such systems, Newey claims that the RB9 retains its front torsion bars, though they are not visible when the bulkhead is inspected.

'The torsion bars are still fitted, but are a bit more recessed in the bulkhead than on previous cars,' he says. 'We have had front-to-rear interlinked suspension on the car for quite a few years – it's a pitch connection which can give some benefits in ride.'

There is some speculation that the RB9 is also fitted with a system that links the suspension diagonally, but Newey would not be drawn on this.

Throughout the car there are many detail changes from the RB8, but one of the most notable lies at the front of the car. A minor rule change relating to the height of the nose at the start of the 2012 season saw all of the cars feature a rather ugly hump. Red Bull uniquely fitted a slot in the nose which it initially claimed was for driver cooling, but later admitted to using for cooling some internal components. It also seemed to have an aerodynamic function as it was linked to a second slot under the nose. A rule change would have allowed Red Bull to fit a non-structural panel in this area, but Newey and his team decided against that approach.

'We do have the vanity panel on there, but it does not stretch the whole way to the front of the



At the time of writing, the RB9 had garnered 11 wins from 17 races, with nine pole positions and 10 fastest laps. Sebastian Vettel won the drivers' championship with three races of the season left

nose as the weight of it would be too high for that,' he explains. 'But we have dropped the letterbox vent which cooled the driver and some electronic systems.'

With the letterbox vent dropped on the RB9, the same solution found on both the 2012 and 2013 Saubers was employed, which featured a vent facing the driver. It is also linked to a slot under the nose.

McLaren's Matt Morris – who oversaw its introduction when he was technical director – explains that its concept is really very simple. 'Everybody is interested in it, but it is something that is not actually worth much performance,' he says. 'When you look at the hump it is clearly not the best dynamic device on the planet, so we just used it to improve the flow in that area.'

One area where every team has struggled to some extent in the last two seasons is the tyres, With the original generation of Pirellis used at the start of the season, the RB9 was often not as strong as many expected that it would be. Then, after the spate of failures at Silverstone during the British Grand Prix, the Italian company was forced to essentially revert to its 2012 tyres. Perhaps as a result of this, the RB9 seemed to make a significant step forward in pace. However, the mid-season tyre change also saw a practice used by a number of teams including Red Bull outlawed. Cars were regularly seen on track with the right rear tyre fitted to the left rear and vice-versa.

'The 2013 tyre construction had ply steel built into it which is a way of changing the toe without changing the toe,' says Newey. 'It's nothing especially magical – by swapping the tyre from side to side you are effectively changing the toe of the tyres. In reality the main benefit was wear management. In qualifying you take a lot out of the tyres – you are driving them as hard as you can and slip can be quite high. On the very heavily handed circuits you take a lot out of the left-hand side of the car typically, so by swapping them for the race you get some benefit.'

'By swapping tyres from side to side you are effectively changing the toe of the tyres – so this was good for wear management'

IN CHARGE – AGAIN

As the European season came to a close at Monza in Italy, the RB9 was – like its predecessors – dominant. Drivers from Mercedes, Ferrari and Lotus soon all admitted that they could not catch Vettel in his RB9, and Red Bull headed into the flyaway races with a seemingly unassailable lead in the constructors' championship. But with the resource restriction agreement in force, the engineers at Red Bull had to not only ensure that the RB9's development rate allowed it to keep its nose ahead, but also make sure that they did not fall behind on development of the RB10.

'We are having difficulty balancing the 2014 development with the 2013 car,' Newey admitted, 'we are dealing with it as best we can. The people working on the long-lead time parts like monocoque and gearbox are exclusively working on 2014 now, and at the same time there is a small team of people working full-time on this year's car.

'It's possible that there may be some small carry-over from RB9 to RB10, but with the size of the changes it's not very much.'

The arrival of the RB10 early in 2014 will draw to a close one of the most successful lines of grand prix cars ever – but it could also mark the start of another equally strong lineage.

Is Red Bull Racing using KERS to enhance mechanical traction?

Red Bull has dominated the F1 drivers' and constructors' championship since 2010. This is often put down to more efficient downforce generation, but David J Dodge believes that the car's advantage is down to a clever way to improve traction. He starts with a few facts and observations:

1. RBR cars are consistently the slowest of the top and mid-field teams in speed traps
2. RBR cars can consistently do the fastest lap times (they have most pole positions)
3. RBR has a higher average speed down long straights, despite having a ~10kph slower top end. They cannot be caught by faster cars
4. In order to have a higher average and lower top speed they must:
   a) have better traction out of the turns
   b) better traction into the turns
   c) better traction though the corners
   d) or all three
5. RBR's superiority is often attributed to the superior aerodynamic downforce Adrian Newey is able to engineer
6. If they had superior aero, they would have more downforce with the same drag and the same top speed or the same downforce with less drag and superior top speed. They don't
7. They are apparently able to take advantage of what appears to be high downforce/high drag setups, while other teams are not able to do so
8. Other teams are not stupid. If sacrificing top end speed for more downforce reduced lap times, they would all be doing it. Does RBR really have a higher downforce setup?
9. Superior aero does not seem to explain RBR dominance. Superior mechanical traction does
10. RBR has had consistent problems with their KERS
11. No other team has had KERS problems since the first year
12. RBR is very technically competent, so why can't they solve a problem that everyone else has solved?
13. They must be doing something different with their KERS
14. They don't appear to be using KERS on the straights (low top end speed). They do appear to be using it at turn exits
15. The mysterious stuttering rubber marks on the exit of the Montreal hairpin may be a clue

In light of these facts and observations, what could RBR be doing that others are not, that gives them a consistent advantage? In other words, what would give them such an advantage and still be consistent with all the above?

The most important clue is their KERS problems. What could they be doing to make it so difficult in comparison to other teams? It must bring a significant advantage, or they wouldn't bother with the complexity.

So here we go! It is theoretically easy to modulate the output torque and charging input torque to an electric motor/generator using capacitors, batteries, inductors and a feedback signal. Torque changes are instant and control is easy. Here are a few things that RBR could be doing with a more sophisticated KERS:

1. If torque were to be modulated in response to the normal force of the tyres against the track (in response to shock pressure, for example) significant unused traction potential could be recovered during high pressure phases (upside of bumps) and initiation of full wheel spin during low pressure phases (downside of bumps) could be delayed. This would yield better turn exit acceleration, higher cornering speeds and stability, especially on bumpy tracks
2. If torque were to be modulated so that the maximum traction is exceeded for only a very small rotation of the tyre and then relaxed to re-establish a new bond to the pavement, then pushed over the limit again, some additional thermal potential of the tyre could be taken advantage of and lateral grip would be more stable. This would yield better mid-turn grip, stability and speed
3. When the threshold of maximum traction is near, the modulation of torque and the consequent slip-catch would give the driver feedback on impending loss of grip. (Note: this may be a violation of the rules.) This could yield fewer driver mistakes and allow them to stay closer to the limit
4. Charging input torque could also be modulated to enhance rear wheel traction during braking. This could yield more effective rear braking, and delay the onset of rear wheel lock-up
5. This does not appear to violate any rules (except for No 3 above). It is traction enhancement, not traction control. Almost everything an F1 team normally and legally does is to enhance traction

Mark Webber's RB9 at the Nürburgring in July 2013

LAT

ADRIAN NEWEY RESPONDS

Racecar highlighted the points raised here with Newey who seemed a little cagey about it all, though he hinted that while the RB5-RB9 line does indeed seem to have low end of straight speed, and relatively high mid-straight speed, this is not down to the usage of KERS.

'I doubt the gain is from KERS,' he says. 'We, like everyone, do work on how to best deploy it, but I think everyone is similar in how they use it. Is our traction better than others? I think it depends on the particular corner leading on to the straight.'

A winning formula

Freeform Technology uses CGTech's VERICUT, the world's most advanced independent CNC tool simulation and optimisation software, to provide peace of mind and a safety net for its machines

Established in 2008, the majority of Buckingham-based Freeform Technology's work is connected to the motorsport industry. This might be expected as its co-directors knew each other when they both worked at Red Bull Racing. Company director Simon Burchett, explains: 'At least 80 per cent of our work is F1, and then there's the non-F1 side of it that's still motorsport. The balance is made up of subcontracts and composite companies that need additional capacity or pattern machining. Many have their own pattern shops, so we act as an overflow capacity for them.'

Having decided to form a subcontract engineering company, the directors were well aware that while the metal-working side offers huge opportunities, there were also many companies who wanted to do it, making it a ruthless industry sector with high start-up costs. Subsequently the decision was made to focus on producing patterns and moulds for the ever-increasing composite components market.

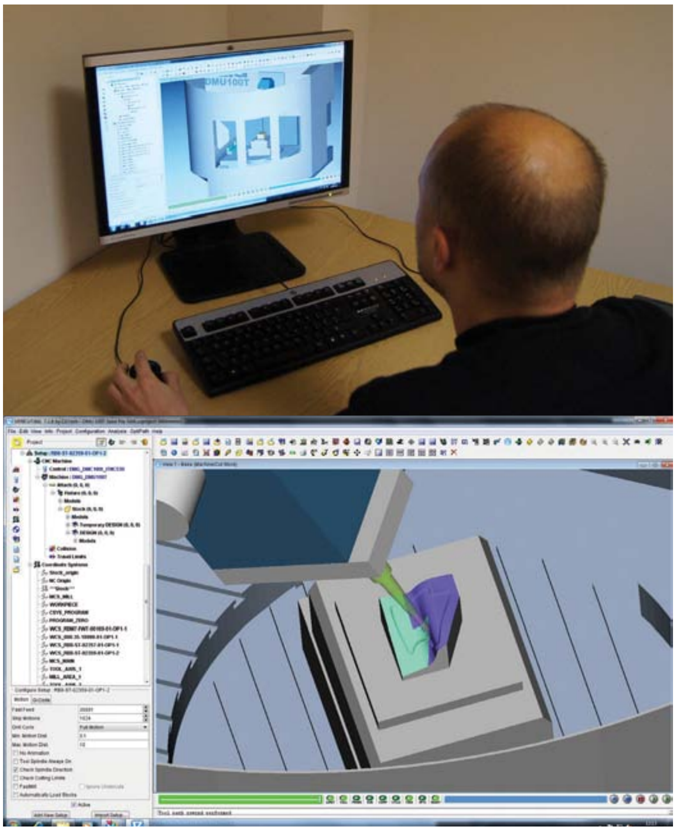
The Red Bull pattern shop had three Breton machining centres. 'The first thing we did was go to the company that supplies them to work something out,' Burchett recalls. 'However, the finance package was beyond us at the time, so that was a non-starter. We looked at second-hand machines, but nothing suitable was available, so we approached CMS Industries. The price seemed more reasonable and we flew out to their factory in Milan, Italy. We were very impressed with the company so we came back to get the finance in place, bit the bullet and re-mortgaged the house just at the start of the global recession.

'Fortunately for us, Red Bull did help us out with work and free-issued material. We have found that like Red Bull, many of the F1 teams we have worked for are very mature and supportive. They really appreciate a supplier that does good work and they don't want to lose them, so they'll do what they need to do to make sure you keep going.'

The new CMS machine came with a warranty of 3000 hours or 12 months, whichever came first – and not many businesses hit that in the first year. Freeform clocked it up within nine months due to the fact that it had to keep it constantly running. 'It was our only machine, our only source of income. We were working from 6am until midnight, and if at any point in the first year that machine went down, we would have gone bust,' says Burchett.

Having used VERICUT at Red Bull, both partners were keen to invest in the simulation and optimisation software. 'We could not afford it until the second year,' says Burchett, 'and going home at night leaving the machine running wondering what you would return to in the morning was quite worrying.

'We always had VERICUT at Red Bull, as it was part of the process, so to not have it was stressful to say the least. As soon as we could afford it, we invested in the software because it is not just for big businesses. With only one machine, you have to protect it. If it goes down, you are effectively unable to work, and when the machine breaks it cost so much to fix. After a major breakdown you think 'with that money I could have had VERICUT'. We felt it was a false economy not to have the level of protection offered by the software. Other small companies see it as a massive overhead – we see it as an essential tool of cost-cutting and survival in the long run.'



Jake Oliveira, CAM programmer, applied VERICUT NC simulation to the company's 5-axis DMG machining centre

Every one of the 13 staff at Freeform will push the start button, go home and be confident to let the NC program run until the end of the machining cycle. 'And,' adds Burchett, 'the quality of work we provide would be affected by a machine tool that had suffered a crash, because the

'There is no point cutting a piece of material for three or four hours for it to be wrong, because the cost of doing that is considerable'

accuracy of the machine will be affected. So as soon as we could get VERICUT there really was no hesitation.'

After turning over a modest profit in the first year, the company purchased another machine tool and started to employ highly skilled staff. Although the company was tight on floorspace, a project for Renault F1 (Lotus F1) for brake ducting components required around 18 patterns. This made the investment crucial. The tolerances were very tight because any air leak would reduce efficiency. A new DMG machining centre was purchased to meet the project demands, and to also provide the ability to machine metallic components. Today the company operates three CMS machines as well as two DMG machining centres.

Every NC program has to pass through VERICUT to ensure the safety of the machine tools. VERICUT supports Freeform Technology's production of complex moulds and composite patterns for the motorsport sector

Native Siemens NX 3D CAD models are supplied by most customers. 'We've had VERICUT for just over three years and its performance is always robust,' says Burchett. 'It's always been what you think it's going to be – very accurate – and it's not going to throw up any sort of spurious mistakes. Using the latest version of VERICUT we've noticed the difference in verification speed, it has been reduced considerably and we can leave it run overnight.'

Four staff at Freeform carry out programming and verifying tasks, but the company is looking to train more people because at busy times it can become a bottleneck. 'Having four people programming with two VERICUT licences is never going to be that easy,' says Burchett. 'We will need another licence, but I don't have a problem paying for it. We see it as a working overhead – it is a key investment as far as we're concerned, having a machine that is smashed up and unable to make the parts accurately is a liability.

'There is no point cutting a piece of material for three or four hours for it to be wrong because the cost of doing that is considerable. It's not just the cost of remaking the part, it's the cost of not being able to do another job while you are waiting for that one to be finished – again. Our objective is to make sure what goes on the machine comes off right the first time. Mistakes upset the customer, ruin your machine and business, and a five minute lapse of concentration that leads to a mistake can effect a week of work. It becomes counter-productive. Staff then have to work longer hours and get tired, the morale drops and the standard of work declines.'

For Freeform, VERICUT simulation and optimisation software is as important as its CAM package. 'We've got to have faith in our CAM package,' says Burchett. 'When we do a tool path it's not going to gouge the part for some random reason as we apply complex tool paths. We have 100 per cent confidence in NX and 100 per cent confidence in VERICUT, so it's almost like an additional safety net for us. Our staff are also confident, which allows them to do one job, leave it and then setup their next job.'

Freeform prides itself on the fact that it has earned a good reputation for delivering quality, and has never delivered anything late. 'We have – admittedly – stretched the day. most people would say the working day ends at five, we'd say midnight, says Burchett. 'Even if there's just a slight change to the tool path, nothing goes on the machine tools unless it has been run through VERICUT first – purely and simply because it is safe.

'As soon as we got VERICUT, we could programme to run through the night, knowing we could leave the machine running for the extra hours and it would be safe. Sometimes we come in the morning and the machine is still running. If we didn't have VERICUT, there is the chance you are going to come in, the machine has mangled the part which cost thousands, the job's not done, your customer is not happy, you're not getting paid, the machine is broken and is going to cost to repair. So for us, not having VERICUT was not an option and also we can sleep at night.'

Revolving doors

They came, they saw, and some stayed. A look back on the recent arrivals and departures from the Formula 1 grid

The V8 era has seen a number of teams come and go as initiatives were introduced to limit the spending which encouraged new entries, although there were some that fell by the wayside as the cost cap was raised in 2010.

Under FIA president Max Mosley, an initiative was introduced in 2009 to limit team spending to £30m per year. Teams signing up for the optional cap would do so in exchange for greater technical freedom, including constantly adjustable wings, engines with no rev limit, a more powerful KERS system and, in theory, four-wheel drive should they choose it. Teams would also be allowed unlimited out-of-season track testing with no restrictions on the scale and speed of wind tunnel testing. The minimum weight of cars was also introduced, moving from 605kg to 620kg to offset those running KERS, and new for 2010 was also a ban on refuelling, designed to reduce travel and staff costs.

Excluded from the cost cap were driver salaries, fines or penalties imposed by the FIA, 2010 engine costs, any expenditure that the team could demonstrate has no influence on its performance, and dividends.

The plan did not meet with the success that the FIA had hoped for. Lola was one of the companies that bid for entry to the F1 World Championship in 2009. The company was not awarded the entry, to the fury of company director Martin Birrane, who later committed his comments to print in *Racecar Engineering, V22 N11*. 'Lola's Formula 1 bid was a positive project for Lola Cars International,' he said. 'I personally funded the whole programme through Lola F1 Team Limited, and we were ahead of all of the competition having assembled the key personnel and provided the engineering services, materials and wind tunnel facilities to proceed. We had a wind tunnel model with the basic external shape defined, and we completed over 90 data runs in the tunnel. History shows that of the three teams chosen, two were uncompetitive and have since been sold, and one never appeared. I very much regret not being awarded a licence because I know with absolute certainty that had we been awarded one, the funding was available and I believe that we would have produced a very competitive car.'

MORPHING TEAMS

The V8 era began without the high spending BAR team, which went west along with Jordan and Minardi as the new engine formula was brought in. Paul Stoddart ran the team for five years, before he sold it to Red Bull in 2005, and the drinks company started the Toro Rosso team that competes today. Jordan was sold to the Midland Group early in 2005 and the Group continued the name 'Jordan' until 2005, when it changed to MF1 racing, and then Spyker in 2007. That outfit was then sold again, becoming Force India in 2008.

Honda first acquired a stake in BAR, and then took 100 per cent control until a dramatic announcement arrived, in the winter of 2008, that the team would no longer continue. Team principal Ross Brawn, with dedication from a slimmed-down team, continued with the car, which featured a double rear diffuser and dominated the early part of the 2009 season, enough for Jenson Button to claim the drivers' title at the end of the year.

In 2009, Mercedes acquired a 75.1 per cent stake in the team, renamed it Mercedes GP, and went on to achieve such heights as setting eight pole positions in nine races during the 2013 season, a feat that earned them the cover of the current issue of *Racecar* (*V24N1*).

BMW's involvement in F1 was not the long-term future that the German manufacturer had hoped for. The team acquired a stake in Peter Sauber's outfit in 2006, but sold it back to its Swiss founder in 2009. The team won just one race – Robert Kubica – in Canada 2008, before the results tailed off towards the end of the season.

HRT

The Hispania Racing Team was one of the few that entered the championship under the cost cap formula. It began as a collaboration between Adrián

Campos, who ran a successful team in lower formulae, and Enrique Rodríguez. The team gained funding through high-profile shareholders, and aimed to become the first Spanish team to enter the championship in 2009. The management of the team was in Madrid, the technical facility at Campos's workshop in Valencia, while in 2009 there was a deal agreed to build a new purpose-built facility. Dallara built the chassis, Cosworth supplied the engines and – along with US F1 and Manor Grand Prix – it entered the Championship in 2010.

However, financial problems led to José Ramón Carabante taking over the team, and installing Colin Kolles to replace Campos in early 2010. The team was named HRT and competed in the World Championship between 2010 and 2012 before the team sold its assets to Teo Martin, owner of a firm specialising in recycling automotive parts.

US F1

One of the teams that attempted to hit the grid in the era of cost capping was the US F1 team in 2010. It was not brought in under the cost-cap regulations – planning for the team had started in 2006, with initial plans based around the need to provide $48m entry bond under the then Concorde Agreement.

Led by engineer Ken Anderson, the plan was simple: go to Companies House in London and get the financial results from Williams that had been posted there from 1997, and base the budget around that. In 1992, Williams developed the FW14 with a workforce of 180 people and a budget of £30m.

The car was due to be built with a Cosworth engine, EMCO gearbox which allowed for very tight packaging, JRI dampers at the front, standard at first but with developments already in the pipeline before the car was launched and a zero keel chassis. Reductions in the price of computing allowed the team to create powerful CAD workstations for a fraction of the cost that they were a decade previously, which allowed it to design in incredible detail for the time.

The team also bought in a lot of crash-testing equipment, to circumnavigate the extremely restrictive rules.

MANOR GRAND PRIX

The plans for the British team to enter F1 essentially started in 2007, when owner John Booth was bought out by Tony Shaw. Two years later, it was announced that Manor intended to contest the Championship, renamed as Virgin Racing and now competing under the Marussia banner.

The team is not a front runner in 2013, but is one of the few new teams that is still on the grid. It has run Cosworth engines for the last three years, taken on a new Xtrac gearbox in 2012 that saved considerable weight and targeted beating Caterham. As reported in issue *V24N1*, the team has secured a new agreement with Bernie Ecclestone to receive guaranteed payments even if it does not finish in the top 10 in the constructors' championship. The deal means that will help to attract sponsorship and the team now expects to stay in F1 until at least 2020. 'It quite clearly would lead to questions when we're looking at potential partners and sponsors for the future,' said sporting director Graeme Lowdon. 'The biggest thing is external perception. We're perceived to be on the same grid, in the same pit lane as every other team now, and it has just removed some of that uncertainty.'

Top: the ill-fated HRT F1 team, which competed from 2010-12, holds the record for the most starts without scoring a point. Centre: Jordan became Midland, and then in 2007 competed as Spyker (pictured) before being bought out by Force India. Above: Toro Rosso, formerly Minardi, debuted in 2006

Teams signing up for the optional cost cap would do so in exchange for greater technical freedom

Boosting straight speed

The ingenious way of stalling the rear wing and achieving significant straight-line gains

BY SAM COLLINS

Replaced by DRS for 2011, one innovation was still present on the Red Bull RB6, which is discussed in the new 'owner's manual' from Haynes Publishing. The following is an extract from it:

The F-duct was an innovation for 2010, first developed by McLaren. The system appeared on the RB6 for the first time at the Turkish Grand Prix in May. Adrian Newey explains the system's origins: 'Really it was experimentation. The F-duct technology actually stems from the Cold War in the 1950s, when the Americans were worried that the Russians would develop ways of jamming the electronics on their fighter aircraft, and so they developed, effectively, a pneumatic version of electronics. So an F-duct is actually a transistor, but using air rather than electricity.'

Although a high level of rear downforce is desirable under certain circumstances (on slower, low-grip circuits and when cornering), on a high-speed straight ultimate speed is compromised by a high level of downforce, as a high downforce wing produces a high level of drag.

The idea behind the F-duct was to provide the car with a straight-line speed boost by temporarily reducing the drag created by the rear wing. Two elements are used on the rear wing to prevent the wing from stalling, by creating a slot to allow high-pressure air to bleed through. So, if this effect can be reversed, and the wing can be deliberately stalled, drag (and downforce) will be reduced and straight-line speed increased. Of course, this is only desirable in a situation when downforce is not so important – such as on a long straight – so the effect needs to be temporary, or 'switchable'.

An attempt to achieve this effect was first made during the 2004 season, when several teams used 'flexible' rear wings, which allowed the slot between the two elements to close up under high load (for instance, on a high-speed straight), stalling the wing. From the 2006 Canadian Grand Prix, by regulation rigid separators had to be fitted between the wing elements to prevent them from flexing.

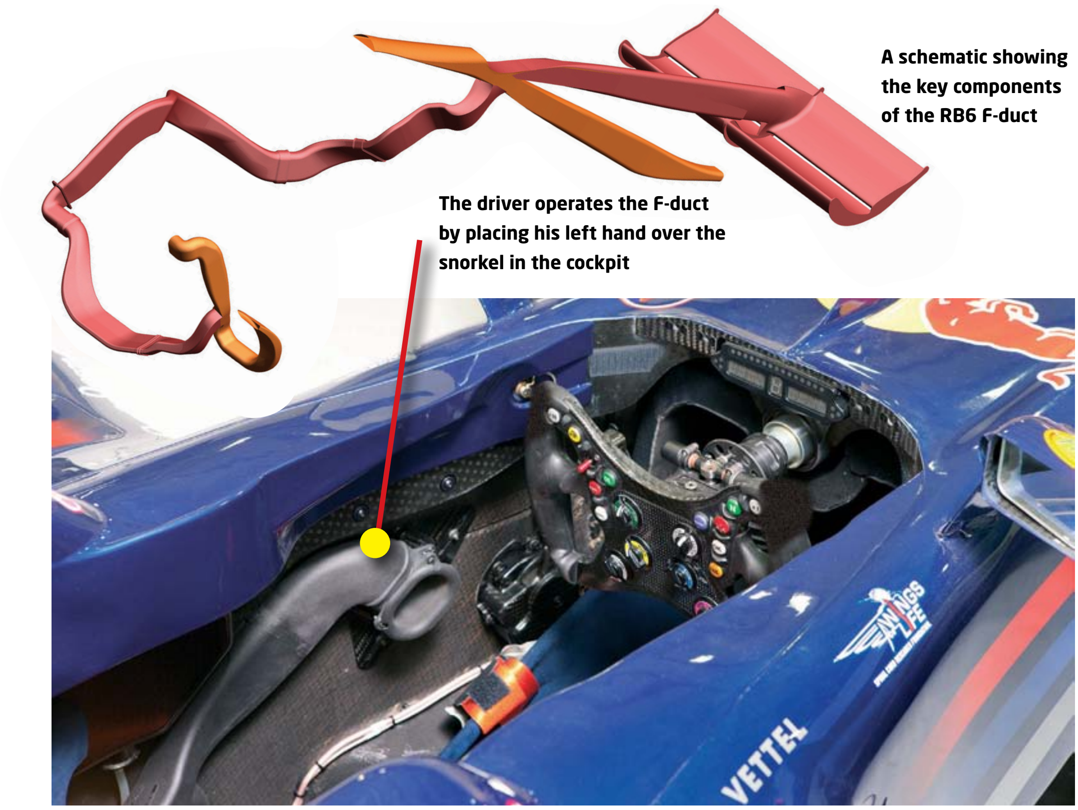
'The technology actually stems from the Cold War in the 1950s'

The F-duct achieved the same effect as closing up the slot between the wing elements, by temporarily allowing extra air to flow over one of the elements, causing the airflow to separate from it and hence stall it. It was found that this could create a top speed increase of up to 4mph.

The key to optimising the F-duct system was to develop a rear wing design that stalled under the influence of the f-duct, but did not compromise downforce when the system was not in operation. The RB6's system took time to develop, and initially the air from the F-duct was blown over the wing upper element. A reasonable stall was achieved, but at the expense of a small reduction in rear wing performance when the system was not being operated. The system was developed and improved during the season and, at the Japanese Grand Prix, a major revision appeared, with the air from the F-duct being blown over the main wing element rather than the upper element.

The switching of the airflow from the lower to the upper duct in the engine cover is being achieved by using a 'fluid switch' operated by the driver. The basic method of operation is as follows:

- 'Control' air flows into the system ducting through an intake in the right-hand sidepod. In the 'default' position, this air flows out through the 'snorkel' on the left-hand side of the cockpit.
- 'Stall' air flows into the ducting from an intake in the bodywork above the driver's head, above the main engine air intake. In the default position, this air flows out through the outlet in the rear bodywork below the rear wing lower element.
- The driver places his hand over the snorkel to activate the system.
- The 'control' airflow is diverted along the ducting inside the engine cover, where it deflects the 'stall' airflow upwards so that it exits through the void in the rear wing upper element (early season) or over the main wing element (late season). The stall airflow creates turbulence at the rear of the wing element, stalling the airflow.



A schematic showing the key components of the RB6 F-duct

The driver operates the F-duct by placing his left hand over the snorkel in the cockpit

Winged wonders

One of the hottest technical topics during the 2010 F1 season concerned the front wings. Our resident aero expert takes a look at the science and the engineering behind them

BY SIMON MCBEATH

Red Bull may or may not actually give you wings, but its Racing division certainly serves up plenty to talk about on the topic of wings. In 2007 we had controversy over flexible rear wings if you recall, after on-car footage of – intriguingly – the Red Bull's rear wing leaning back at speed was seen on TV and subsequently in video published on the internet.

Our analysis feature on that occasion *(V18N1)* said 'it looked as if those clever F1 engineers had found another way to pass the tests and checks at scrutineering while still providing a degree of flexibility in the installations of the wings.' Then in 2010, the situation was uncannily similar, with the same team (plus Ferrari) coming under the spotlight as footage and photos once again revealed something clever was going on.

We all know that there's more to F1 than ever meets the eye, and that most of the really clever innovations remain forever under wraps. In this case we could see what was going on, even if we couldn't see entirely *how* it was being done. We can, however, attempt to understand properly *why* it was going on.

Visually there were two separate things happening during the 2010 season, up to and most obviously including the Hungarian GP, probably brought about by quite different means. There was the simple flexing of the front wings in response to the aerodynamic loads, wherein the outer portions of the 1.8m wide (70.9in) span wing assembly, suspended from two quite closely spaced pylons under the nose, bend closer to the ground at speed. All centrally

LAT

The flexible front wings caught on camera during the 2010 Hungarian Grand Prix: the front of Sebastian Vettel's RB6 (top) hugs the ground, while Mark Webber's (above) is in flex

We saw the simple flexing of the wings in response to aerodynamic loads, and then the whole front of the car getting closer to the ground than normal

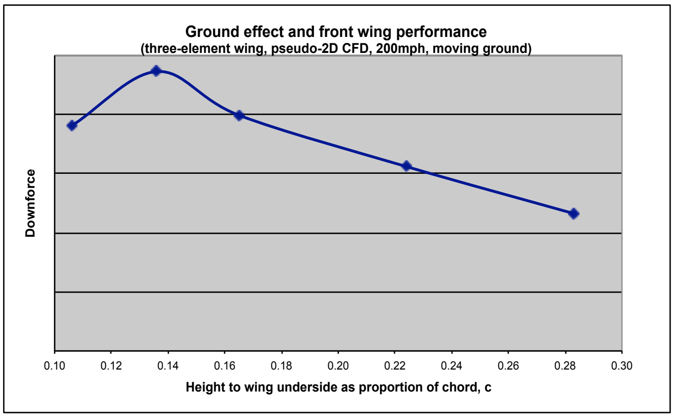


Figure 1: downforce from a front wing increases as ground clearance decreases – but only up to a point

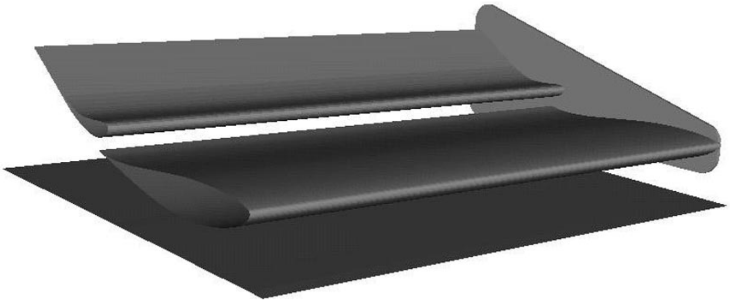


Figure 2: this front wing was evaluated in CFD for Aerobytes in *V15N6*

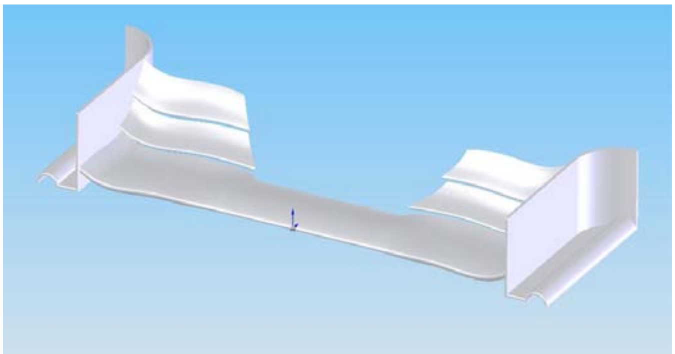


Figure 5: a 2010 F1-style front wing – the forces on the potent outer sections inevitably cause flex at speed

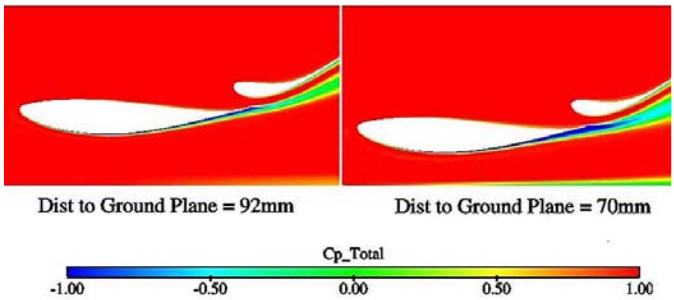


Figure 3: At lower ground clearances the air near to the wing surface loses more energy, as depicted here by total pressure (Cp-total) losses

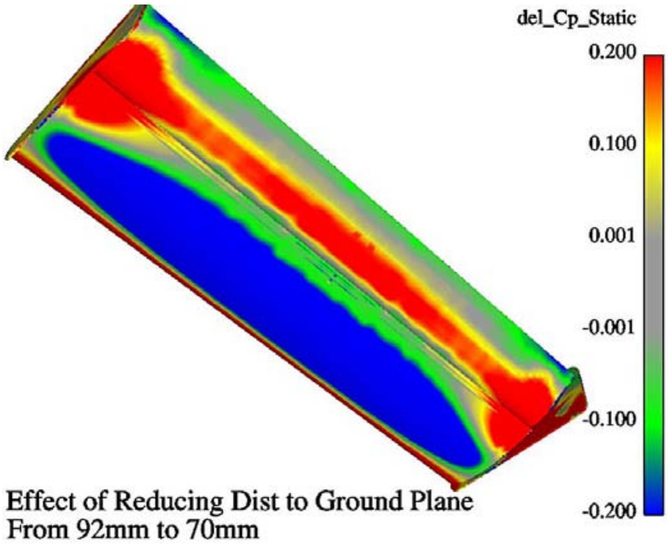


Figure 4: as ground clearance reduces, parts of the wing work better, but the more rearward parts struggle, and ultimately flow separation occurs

mounted wings must do this to some extent, but others clearly do it more. And then there was the rather different matter of the whole front wing – possibly the whole front of the car – getting closer to the ground at speed than seemed normal, and the potential mechanisms by which this might be have been achieved are what really lie at the centre of this controversy. McLaren team principal Martin Whitmarsh commented that his team couldn't understand how this could be done within the regulations, and the precise mechanisms will almost certainly remain a mystery. What we can do, however, is look at the potential benefits and downsides of employing a flexible front wing, and/or getting the whole front wing nearer to the ground.

Front wings on open wheel racecars operate in ground effect, and – as is well known – proximity to the ground amplifies the downforce that can be generated from a given wing, relative to its performance in 'freestream' air, well above the ground. This effect increases the closer a wing gets to the ground, until at a certain height the effect reverses because of flow separation and the downforce reduces again.

The diagram above (top left) is a typical representation of the effect we're describing, derived with 'pseudo 2D' CFD on a three-element wing section, and it illustrates simply how a front wing is sensitive to ground clearance. It also demonstrates why racecar engineers would ideally want to operate the front wing in the region around the peak on this plot, to maximise the performance of the wing and to minimise fluctuations in wing-generated downforce over a relevant dynamic ride height range.

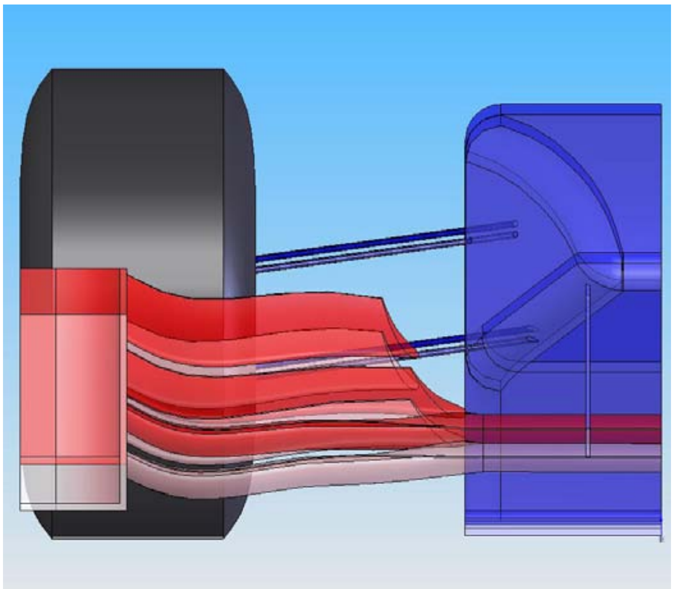
PLAYING BY THE RULES

It's tempting to superimpose some dimensions on to this. The 2010 F1 front wing had a maximum permitted chord (between 400mm and 750mm from the car's centreline) of 550mm. The peak on the graph in the diagram at 0.136c therefore equates to a height above the ground of about 75mm.

The 2010 FIA Formula 1 technical regulations stipulated that the minimum height of any part of the front wing measured statically may not be less than 85mm above the bottom of the un-worn 'plank' (itself 10mm thick and bolted to the so-called 'reference plane'). This might suggest the front wings were about as low as they needed to be. But while this 2D CFD view demonstrates the generic effect, 3D flows are more complex and change the picture considerably, as the next example (which originally appeared in Aerobytes in *V15N6*) shows.

Here a simple two-element front wing was evaluated in a 3D CFD trial at two different ground clearances. Measured to the leading edge these were 92mm and 70mm, which approximated 62mm and 40mm ground clearance to the lowest part of the wing's underside.

The first thing to note here is that the wing was still performing properly at these smaller ground clearances, as would be expected. Secondly, at the lower ground clearance, the wing produced 4.5 per cent more downforce, a significant gain and one not to be ignored. Hence the whole quest to obtain lower ground clearance on what in F1 is compulsorily quite a high mounted front wing. However, it is fair to say that making 'moveable' systems like



Schematic showing the approximate order of wing flex and overall movement believed to have been happening on some F1 cars during 2010

WHY DO FRONT WINGS STALL WHEN THEY GET TOO CLOSE TO THE GROUND?

As air passes under the leading edge of a front wing it accelerates and, as Bernoulli described, its (static) pressure reduces. Then, from the region of minimum pressure under the wing to the wing's trailing edge, the velocity slows and the pressure rises again. This region of rising pressure has what is referred to as an 'adverse pressure gradient', for the simple reason that air much more naturally flows from high to low pressure and not the other way round.

When a front wing is above the critical height identified in **Figure 1**, the air is able to 'climb' this adverse pressure gradient because it has enough energy to do so and the pressure gradient is not too steep. However, as the wing is lowered towards the ground, the pressure underneath gets lower and lower until the critical low height for a given wing is reached, at which point the adverse pressure gradient becomes too steep.

Not only that but, as we see from the trial done on the wing (**Figure 2**), by being worked harder at a lower ground clearance, the air adjacent to the wing surface loses more energy, depicted as total pressure. A steeper adverse pressure gradient and less energy mean the air can no longer 'make the climb'. What ensues is flow separation, where the flow no longer remains attached to the wing surface and instead breaks away before it reaches the trailing edge. The net result is that downforce reduces, and this corresponds to the graph line to the left of the peak in the **Figure 1** diagram.

Although the wing trial shown here produced an increase in downforce at the lower ride height tested, it also illustrated what happens as a wing gets closer to its minimum critical height above the ground. **Figure 4**, the graph on the bottom right is a 'delta Cp-static' plot showing the difference in static pressure coefficients on the wing's suction surface between the two cases.

The blue shows where lower static pressure coefficients occurred at the lower ground clearance; red shows where higher static pressure coefficients occurred at the lower ground clearance. Clearly the mainplane produced more suction at the lower ground clearance, but the flap produced less suction. There was still a net overall gain in this instance, but were the ground clearance to be reduced still further, flow separation would develop. This would then see a reduction in downforce.

these work to your advantage is no simple task, especially given the changing profile of the wing across the span, as well as the proximity of the front tyre, chassis and other downstream paraphernalia.

There is another benefit to be had from allowing the front wing to flex too, and that is to bring the end plate nearer to the ground. Doing this once again strengthens the wing's performance by reducing the amount of air that can flow under the end plates into the low-pressure area beneath wing, which allows more downforce again to be generated.

But according to highly experienced F1 aerodynamicist Frank Dernie, with whom *Racecar* had the opportunity to discuss these matters, this also has an important effect downstream too, because getting that front wing end-plate closer to the ground also reduces the adverse effect that the front wing tip vortex has on the underbody. With the full width front wings that were mandated at the start of 2009, this vortex ran around the outside of the tyres, but it still gets drawn into the underbody further downstream. So not only was the front wing's downforce contribution increased by improving the efficiency of the end-plates, so too was the underbody's contribution. And although the overall gain was predominantly front-biased, it's not all from the front wing.

WING LOWERING

The most contentious aspect of what was seen and photographed on the Red Bulls, however, was the apparent ability to run the whole of the front wing closer to the ground than anyone else. Leaving aside for a moment the really contentious side – how this might be have been done while remaining within the rules – the foregoing explanations on how ground proximity will increase the front wing's downforce provides the 'why', and can also be applied to the rest of the wing's span, even the neutral, symmetrical section across the central 500mm, which also produced downforce when in ground effect.

So not only would the outer portions flex closer to the ground, but the rest of the span got closer to the ground too, which will have contributed to a more

HOW DO FRONT WINGS FLEX?

Making a front wing flex under load isn't complicated in principle, but the R&D effort required to enable it to do so predictably and controllably must be considerable. As Frank Dernie commented: 'Toyota ran with a flexible front wing all through 2009 and it took a long while to get the lay-up right.'

So it was about engineering the composite lay-up of the wing to obtain the degree of flex required, and to remain within the regulations – or to pass the scrutineering tests, if these requirements are thought to differ...

Looking at an F1-style wing, it's clear that the aerodynamic load that is generated by the outer portions will be considerably greater than that generated by the central portion, about which the structure will effectively flex. But the overall aerodynamic force vector on this outer section, which is the combination of vertical and horizontal aerodynamic forces, sets up a twisting load on the centre section that, were the structure not designed to resist it, would see the rear of the end-plate get nearer to the ground under load. This would also decrease the angle of attack of the outer part of the wing, which is clearly not the current aim.

So the lay-up of the wing must resist this torsional load, but allow 'beam' flex across the span of the wing. Altering the thickness and the direction of the fibre orientations in the reinforcing carbon fabrics – for example to align at +/-450 relative to the wingspan – are well-used methods in achieving the desired structural properties.

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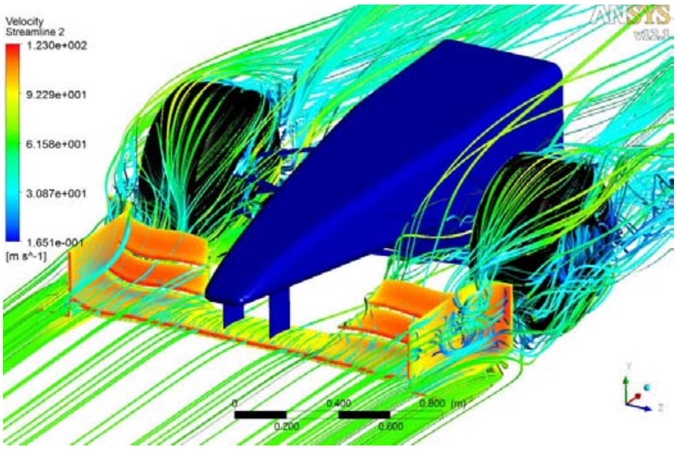
significant gain in front end downforce than flexing the tips alone, according to Dernie. We still wonder at just how this additional forward-biased downforce will have been balanced, but the Red Bulls (and Ferraris) certainly did not look unbalanced, which serves to illustrate how good those cars were overall, notwithstanding any front wing trickery.

Dernie observed that there is one inherent disadvantage of using the aerodynamic forces to reduce the ground clearance over some of, or the entire, front wing, and that is that the maximum effect is at the fastest speeds, which are on the straights and therefore the maximum benefit is not where it's necessarily wanted.

However, total drag does not increase with increased front wing downforce so there was no penalty in that sense. And although braking at the end of straights may possibly have been enhanced (unless the tyres are already 'saturated' with downforce, to use a Dernie expression), the maximum downforce benefit may not have been available when it was most needed – between coming off the brakes into a corner and re-applying full throttle at corner exit.



Some sense of the complexities in the flows around the wing tips and the front wheels was derived using Ansys CFD-Flo on this F1-style front-end model. The wing is coloured by pressure, the streamlines by velocity

Countering this point, another well-known former F1 designer, Gary Anderson, suggested in *Autosport* that when a flexible front wing starts to generate flow separation as it approaches the ground, the loss of downforce will then regulate the wing height by allowing the wing to flex back up again. In contrast, he surmised, a rigid front wing will compress the front suspension as it loads up, but then as it starts to see flow separation at lower ground clearances and lose downforce, it will be the car that rises back up on its suspension, rather than the wing, so causing the car to bounce.

According to Anderson then, a car with a flexible wing will be more benign, the wing finding its own 'happy medium'. Again, if this is the case, considerable R&D would be involved to control the wing's stiffness, or lack thereof, in order to find the sweet spot between un-damped fluttering and excess rigidity – a classic case for fluid-structure interaction (FSI) analysis, no doubt.

So, for those who got it right, how much lap time was it all worth? Published estimates vary from an unlikely sounding second per lap to a more realistic-sounding three-tenths per lap. The reality is probably somewhere between the two. Red Bull's lap time advantage at the Hungaroring in 2010 was, if one averages the two drivers' times, almost exactly a second ahead of the nearest competitor (Ferrari), while the average of their fastest race laps was about seven tenths faster than the nearest Ferrari. Dernie observed that 'the difference in the performance of the Ferraris and McLarens is probably mostly due to the front wing, but the difference between the Red Bulls and the Ferraris is more than just the front wing.'

The best car will be the one that offers the best compromise between absolute downforce and consistent performance to provide the driver with not only good grip but also good feel and confidence. And maintaining a front to rear balance is absolutely crucial. Flexing, moving wings must make this an even more difficult goal to achieve. So the Red Bull's speed advantage in 2010 is unlikely to have been *all* about its clever front wing.

But, every little helps...

HOW DO FRONT WINGS GET NEARER THE GROUND?

Allowing a car's suspension to be compressed by aerodynamic loads enables dynamic ride height to be lower than static ride height, but only up to the point where the lowest part of the chassis underside – usually the front of the consumable 10mm thick 'plank' in the case of F1 cars – touches the ground. How close to the ground is the front of the plank? Frank Dernie: 'You run the car so that the plank stays just within the 1mm wear you are allowed throughout a race.'

So, the plank grounds periodically, but not continually, or wear will exceed this limit. Given then that the rules require that the lowest point of the front wing must be 85mm above the unworn plank, how is it possible to get the central section seemingly much closer to the ground that this when a car is at speed?

Possible explanations that inevitably come to mind, however fanciful, might be:

- A floor passing the upward deflection test yet moving up dynamically, enabling greater compression of the front suspension, and hence lower front wing height.
- A nose that droops, Concorde-style, or deforms at speed, allowing the wing to move closer to the ground.
- Wing mounts that lengthen or deform at speed yet allow static scrutineering checks to be passed.
- None of the other teams is able to run its cars nearly as low as Red Bull Racing did, and the Red Bulls were running legally at all times.

Pick one of the above or add your own theory to the list and let us know about it!

THE FIA TESTS

FIA Formula 1 race director Charlie Whiting told *Racecar* that up to and including the Hungarian GP in 2010: 'we have been measuring deflection at the outer ends of the front wing relative to the nose. It will now be done relative to the reference plane. But the load/deflection criteria will not change – that is 10mm of deflection will be permitted under a 500N load. However, we now reserve the right to increase the load to as high as 1000N and expect to see linear behaviour above the normal test load.'

The first part of this statement is an interesting development because the way in which the test was previously carried out might not have picked up compliance in the wing mountings or the nose. Measuring deflection relative to the reference plane of the car's underside, however, will take into account any deflections in the mounts or the nose (although it could still miss more devious mechanisms).

The current load/deflection criteria stipulated in the regulations involved a 500N (approximately 50kg) load exerted vertically downwards on the outer end of the wing, with a maximum permitted deflection of 10mm.

The threat of potentially having to pass a test where double that force is applied and linear deflection (ie 20mm maximum) is expected may have meant the 2010 summer break was no holiday in the composites departments of some teams...

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Harmony restored

The cloak of secrecy has been lifted from the inerter – but how does it really work and what can it be employed to do?

BY CHARLES ARMSTRONG-WILSON

The secret of mechanical grip is to reduce rapid load variations at the tyre contact patch. This simple truth has been known for years and is the objective of tuning suspension dampers. To this end, teams all over the world run thousands of hours of expensive rig testing time in order to better understand it. More recently, mass dampers have been employed to achieve the same aim, most notably by Renault F1. But it also emerged that the McLaren team had pre-empted their use with its subtle and complex inerter.

The concept for the inerter originated through Cambridge University and Professor Malcolm C Smith's work on electrical and mechanical systems. There has been a long-standing observation that most elements in an electrical circuit have a mechanical equivalent. By viewing a mechanical system as an equivalent of an electrical one, a different perspective can be taken on how it works and how the elements all interact.

There are different views as to how this equivalence should be defined, but for his work Smith has adopted the convention that force is the mechanical equivalent of current and velocity equates to voltage. Likewise, certain electrical components have mechanical counterparts. He equates the mechanical spring to the electrical inductor, the damper to a resistor and a fixed mechanical point to the electrical ground of a circuit. However, he notes that up until now, within his preferred convention, there has been no obvious direct mechanical counterpart to the electrical capacitor.

That said, the mass of a body can be equated to a capacitor under a special set of conditions. That is, it has inertia, but that inertia is relevant to its position in space. In that sense it is like a grounded capacitor whose potential is relative to earth. What did not seem to exist was a mechanical element that could be used like a capacitor in isolation. In other words, with two terminals and the behaviour of which was dependent on the load across those two terminals and not its movement relative to its position in space.

Without this element, it would not be possible to replicate most electrical configurations mechanically.

ENERGY CAPTURE

It was while considering this that Smith came up with the idea of storing kinetic energy rotationally in flywheels. They could capture and release large amounts of mechanical energy, while having an insignificantly small inertia relative to their position. By gearing up the flywheels to increase their speed, a greater amount of energy can be captured without increasing the mass of the device and its inertia in space.

As an attempt to create this effect, Smith started with a configuration as in **Figure 1**. One terminal is mounted on the casing that houses the gears. The other is on the end of a rack that spins a gear that, in turn, spins a flywheel at high speed.

To consider how much energy is stored, we can derive a simple formula. If we define the following:

r1 = radius of the rack pinion
γ = radius of gyration of the flywheel
r2 = radius of the gearwheel
m = mass of the flywheel
r3 = radius of the flywheel pinion

Also, the velocity of the rack is the velocity of one terminal minus the velocity of the other, or:

v = v2 - v1

...then:

α1 = γ/r3
α2 = r2/r1

The resulting equation of motion:

$$\mathbf{F} = (m\alpha_1^2\alpha_2^2)\,(\dot{\mathbf{v}}_2 - \dot{\mathbf{v}}_1)$$

To show how effective this concept can be, if one was to set both α1 and α2 at 3.0, then the inertance factor will be 81 times the mass of the flywheel. From this it is easy to see how the actual inertia of the unit due to movement of its centre of gravity is relatively insignificant compared to the energy that can be captured and released by the device. In fact, one of Smith's first prototypes had an inertance-to-mass ratio of about 300.

In order to use the inerter to successfully damp cyclical

PROFESSOR MALCOLM C SMITH

Having received a degree in mathematics from Cambridge University, Malcolm C Smith stayed on to complete an M Phil degree in control engineering and operational research, and then a PhD in control engineering. Equipped with such a hefty portfolio of qualification, he went on to become a research fellow at the German Aerospace Center, DRL, a visiting assistant professor and research fellow with the Department of Electrical Engineering at McGill University, Montreal, Canada, and an assistant professor with the Department of Electrical Engineering at the Ohio State University, Columbus, USA.
He is now a fellow of Gonville & Caius College and a professor in the Department of Engineering at the University of Cambridge.
His particular research interests are control system design, frequency response methods, H-infinity optimisation, non-linear systems, adaptive control and active suspension.

PETER WRIGHT SAYS

The test for parts of the car that move and may have an incidental effect on aerodynamics was approved by the World Motor Sport Council in 1993, and is that the aero effect must not be significant. This then became the official interpretation of the 'primary/secondary' test that applied to things like fans. Something like a piston – for example – moves, but the aero effect it has is judged insignificant.

In the Renault case, the Appeal Court found that the effect of the mass damper was significant, based on figures supplied by Renault, even if it was secondary.

The other important issue is whether the moving component in question is part of the suspension or not. The mass damper was deemed not to be, while the J-damper undoubtedly is. This is why it is permitted, whether it has a significant aerodynamic effect or not.

Peter Wright is a consultant to the FIA and technical consultant to Racecar Engineering

INERTERS

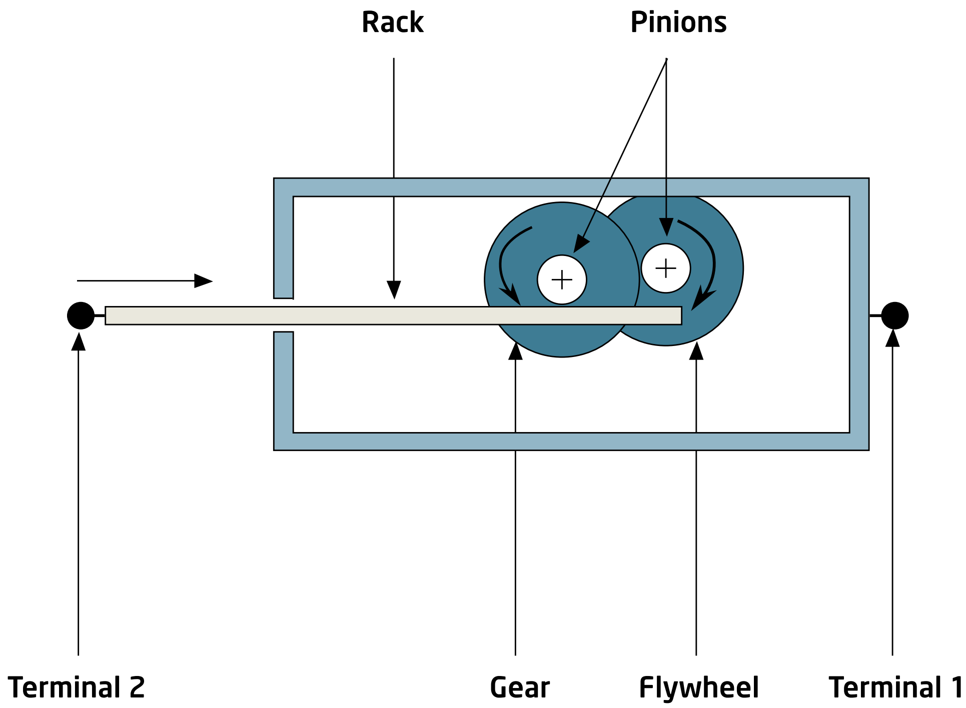

FIGURE 1
Mechanical interpretation of the principles of the inerter. One terminal is mounted on the casing, the other on a rack that drives a pinion as it moves in and out. The pinion drives a flywheel via a larger gear producing high rotational speeds and capturing large amounts of inertial energy compared to the mass of the whole unit

MECHANICAL	ELECTRICAL
$Y(s) = \frac{k}{s}$; $\frac{dF}{dt} = k(v_2 - v_1)$ spring	$Y(s) = \frac{1}{Ls}$; $\frac{di}{dt} = \frac{1}{L}(v_2 - v_1)$ inductor
$Y(s) = bs$; $F = b\frac{d(v_2 - v_1)}{dt}$ inerter	$Y(s) = Cs$; $i = C\frac{d(v_2 - v_1)}{dt}$ capacitor
$Y(s) = c$; $F = c(v_2 - v_1)$ damper	$Y(s) = \frac{1}{R}$; $i = \frac{1}{R}(v_2 - v_1)$ resistor

TABLE 1
The three main electrical components and their mechanical equivalents. Until the invention of the inerter there was no mechanical equivalent of the capacitor

behaviour in a car's suspension it is necessary to tune the device to the frequencies likely to be encountered in the system. In Smith's words, 'We define the ideal inerter to be a mechanical, one-port device such that the equal and opposite force applied at the nodes is proportional to the relative acceleration between the nodes.'

Put mathematically:

$$F = b(\dot{v}_2 - \dot{v}_1).$$

The constant b is the inertance measured in kg and equates to McLaren's 'zogs'. This was all part of the team's efforts to keep its new technology secret. Firstly, the team christened its inerter a J-damper, or jounce damper, as was revealed in the secrets to Renault case. Then, rather than using the term inertance – which would have been a big giveaway in the pits if anyone overheard it – the engineers came up with the term zog. In pit garage parlance, 'can you change to a 50-zog J-damper.' The actual relationship between zogs and kg is still only known within the key people at Woking.

Getting this relationship right, however, is critical, not only to making the J-damper work effectively, but also to avoid huge loads should the damper and the suspension start cycling together. In the worst case it could rip the damper and even the suspension apart. Indeed, some believe this was the cause of Felipe Massa's suspension failure at Monza in 2007, as Ferrari struggled to come to terms with the new technology.

The stored energy in the inerter is calculated using:

$$\frac{1}{2}b(v_2 - v_1)^2.$$

Here, b is the inertance and would typically be given in kg. This completes the battery of mechanical equivalents to electrical components as shown in **Table 1**.

Like a conventional suspension damper, the ideal inerter for a suspension system can be approximated by calculation.

Compared to the mass damper, the inerter is mounted differently within the suspension.

MASS DAMPING

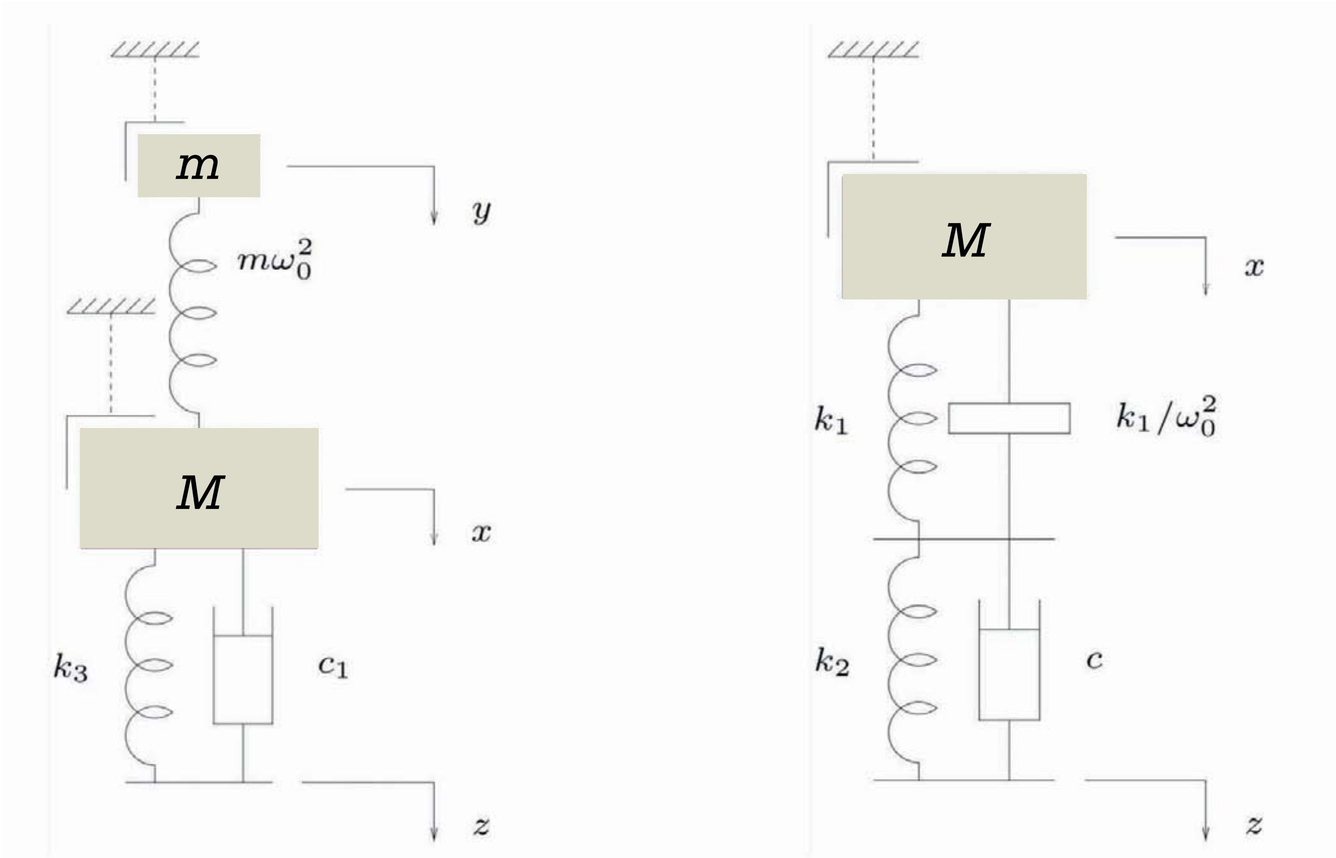

FIGURE 2
On the left is the normal arrangement of a mass damper (m) being used to stabilise a larger sprung mass (M).
In contrast, the schematic on the right shows how an inerter is used to achieve the same effect

In **Figure 2**, the mass damper (m) is attached to the sprung mass (M) and uses its inertia relative to its position in space to exert an opposing force on the main mass to calm its motion. In contrast, the inerter in **Figure 3** between the mass and the exciting force can absorb and return mechanical energy in harmony with and opposing its movement.

So, to recap, what Smith has devised is an ideal mechanical inerter with two terminals and the relative acceleration of those terminals is proportional to the force on them. Crucially, it behaves like a normal two-terminal capacitor. In contrast, conventional mass dampers can only be considered as the mechanical equivalent of grounded capacitors because their acceleration is relative to a fixed inertial frame. He also proposed an inerter design that has an insignificant mass compared to the energy it is capable of storing.

His design is a simple mechanical system that can be constructed in a number of ways, driving the masses with a rack or a spiral, and a mechanical advantage can be built in that creates very high rotational energy. Its key advantage is that it acts very differently to springs and dampers. These act after the event in that they need movement to operate, so can only act after the external input has been applied. However, the inerter – by operating in harmony with the natural frequencies of the suspension system – can anticipate the input. That way movements and load variations can be cancelled out before they occur. Translate that into the conditions at the contact patch of the tyre and it can be seen how it will stabilise load variations and allow the rubber to generate maximum grip.

Going back to the mass damper, this was banned on the grounds that it had an influence on the attitude of the sprung part of the car. As this is, in itself, an aerodynamic device, it was decreed that the mass damper was a movable aerodynamic device and illegal under the Formula 1 rules. But surely by reducing cyclical behaviour in the suspension, couldn't the inerter also have an influence on the attitude of the car and, therefore the aerodynamics? The answer is certainly yes, yet the device has not been deemed illegal by the FIA.

All this demonstrates that the real reason for outlawing mass dampers was the safety concerns of having several kilos mounted on springs in the nose, a part of the car that often becomes detached. The inerter, mounted on the main part of the car and weighing comparatively little, was not

Professor Smith devised an mechanical interter with two terminals, and their relative acceleration is proportional to the force on them