Design of a
Racecar

Modern racing technology – the inside story

Design principles • Optimisation • Metrology • Machining • Wind tunnels • Testing

From the experts at Racecar engineering

ISSN 2634-4939 £9.99

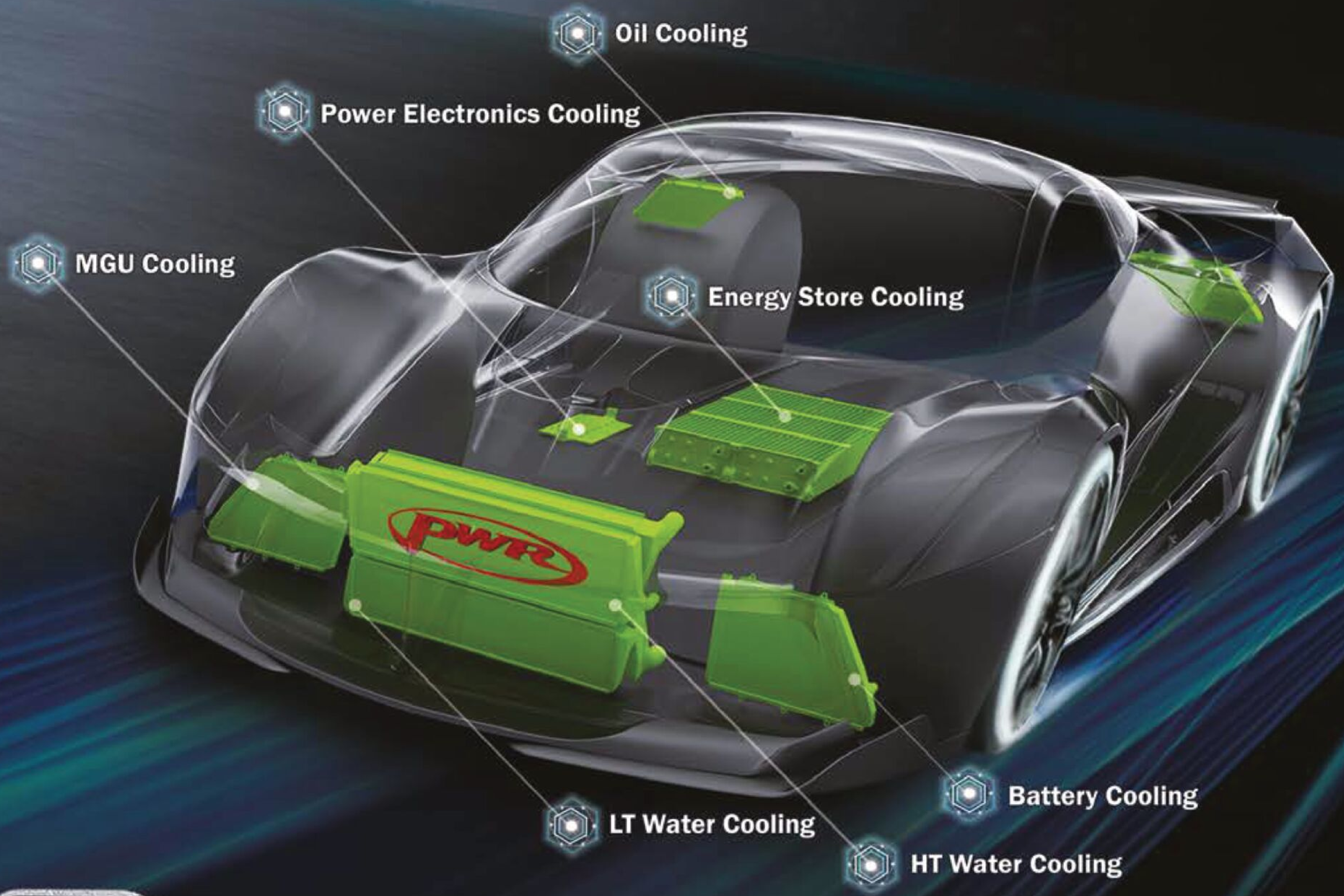
01

9 772634 493008

PWR
ADVANCED COOLING TECHNOLOGY

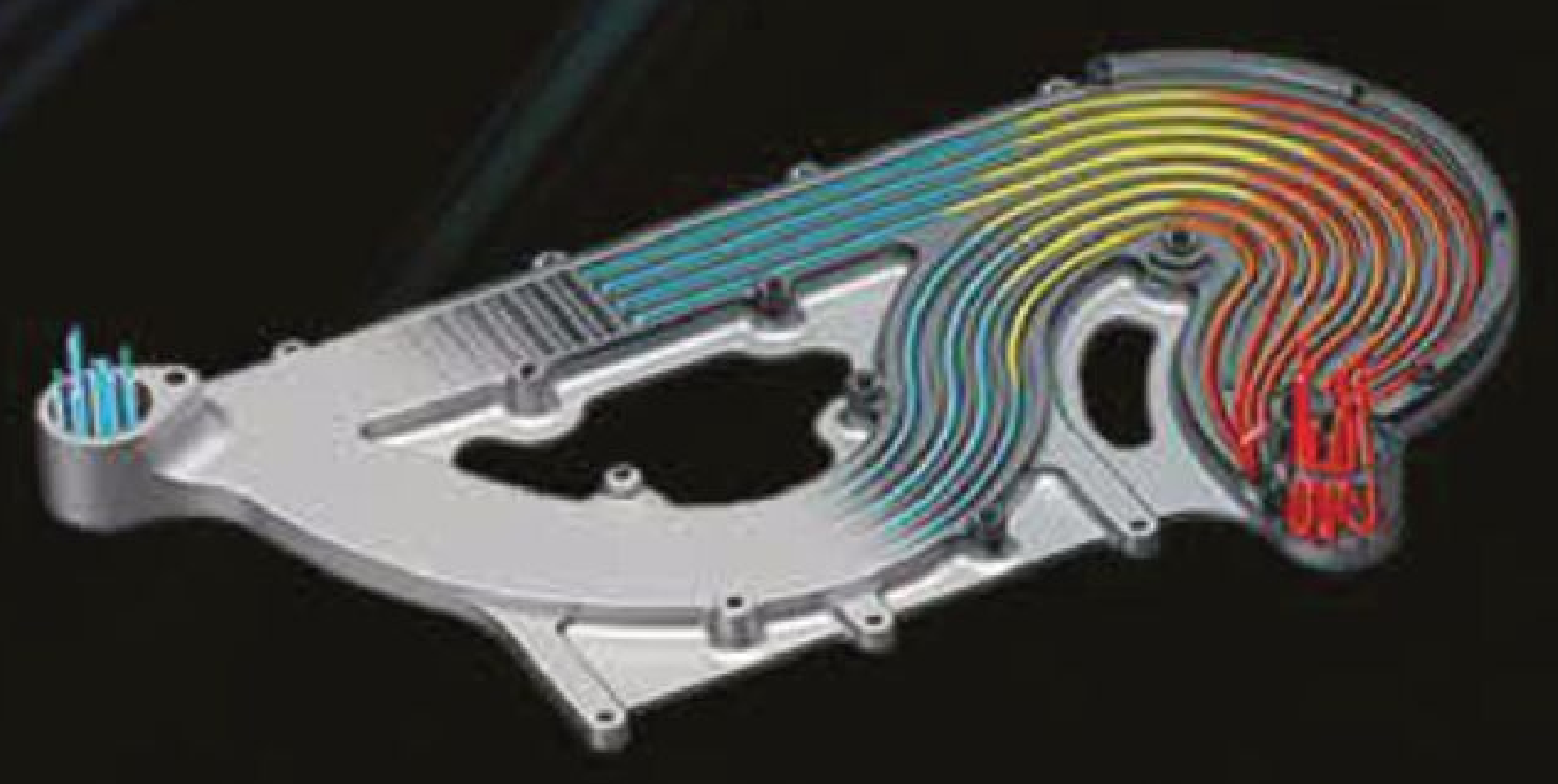
System Simulation | Design | Manufacture | Calorimeter Testing

From initial concept, through to performance verification and production, PWR is your global solutions provider servicing all ICE, Hybrid and EV Cooling system requirements. By coupling advanced system simulation and test tools with latest technology manufacturing processes including additive manufacturing and unique vacuum brazing capabilities, PWR is your engineering partner for optimisation and production of all your cooling requirements.



PWR has partnered with VELO3D using their Sapphire machine technology and unique "SupportFree" processes enabling class leading thin wall capabilities and high quality surfaces without porosity. PWR manufacture higher quality internal channels, flow paths, and high aspect ratio walls for new designs that optimize heat transfer.

While conventional 3D printing systems often require supports for any geometry below 45°, PWR & VELO3D's Sapphire uniquely enables designs to be realized with overhangs down to 0° (horizontal), and large inner diameters without supports. PWR & VELO3D's Sapphire is the next generation metal additive manufacturing system designed to unlock Digital Manufacturing for mission critical applications.



PWR manufacture ruggedized liquid cooling plates and brazed chassis for Aerospace, Defence, Automotive and Motorsport markets. These components are used in a variety of end applications such as radar systems, autonomous vehicles, energy storage systems and power electronics cooling applications.

www.pwr.com.au | cooling@pwr.com.au | Australia | USA | Europe

Design of a
Racecar
Modern racing technology – the inside story

Editor
Andrew Cotton
@RacecarEd

Deputy editor
Stewart Mitchell
@RacecarEngineer

Chief sub editor
Mike Pye

Art editor
Barbara Stanley

Technical consultant
Peter Wright

Contributors
Lawrence Butcher,
Jahee Campbell-Brennan,
Ricardo Divila, Gemma Hatton,
Simon McBeath

Photography
James Moy

Managing Director - Sales Steve Ross
Tel +44 (0) 20 7349 3730
Email steve.ross@chelseamagazines.com

Advertisement Manager Lauren Mills
Tel +44 (0) 20 7349 3796
Email lauren.mills@chelseamagazines.com

Circulation Manager Daniel Webb
Tel +44 (0) 20 7349 3710
Email daniel.webb@chelseamagazines.com

Subscriptions and Marketing Manager
Luke Chadwick
Tel +44 (0) 20 7349 3700
Email luke.chadwick@chelseamagazines.com

Publisher Simon Temlett

Managing Director Paul Dobson

Editorial and advertising
Chelsea Magazine Company,
Jubilee House, 2 Jubilee Place,
London, SW3 3TQ, United Kingdom
Tel +44 (0) 20 7349 3700
Fax +44 (0) 20 7349 3701

***Racecar Engineering* subscriptions**
Tel: +44 (0)1858 438443
Email
racecarengineering@subscription.co.uk
Online
www.subscription.co.uk/chelsea/help

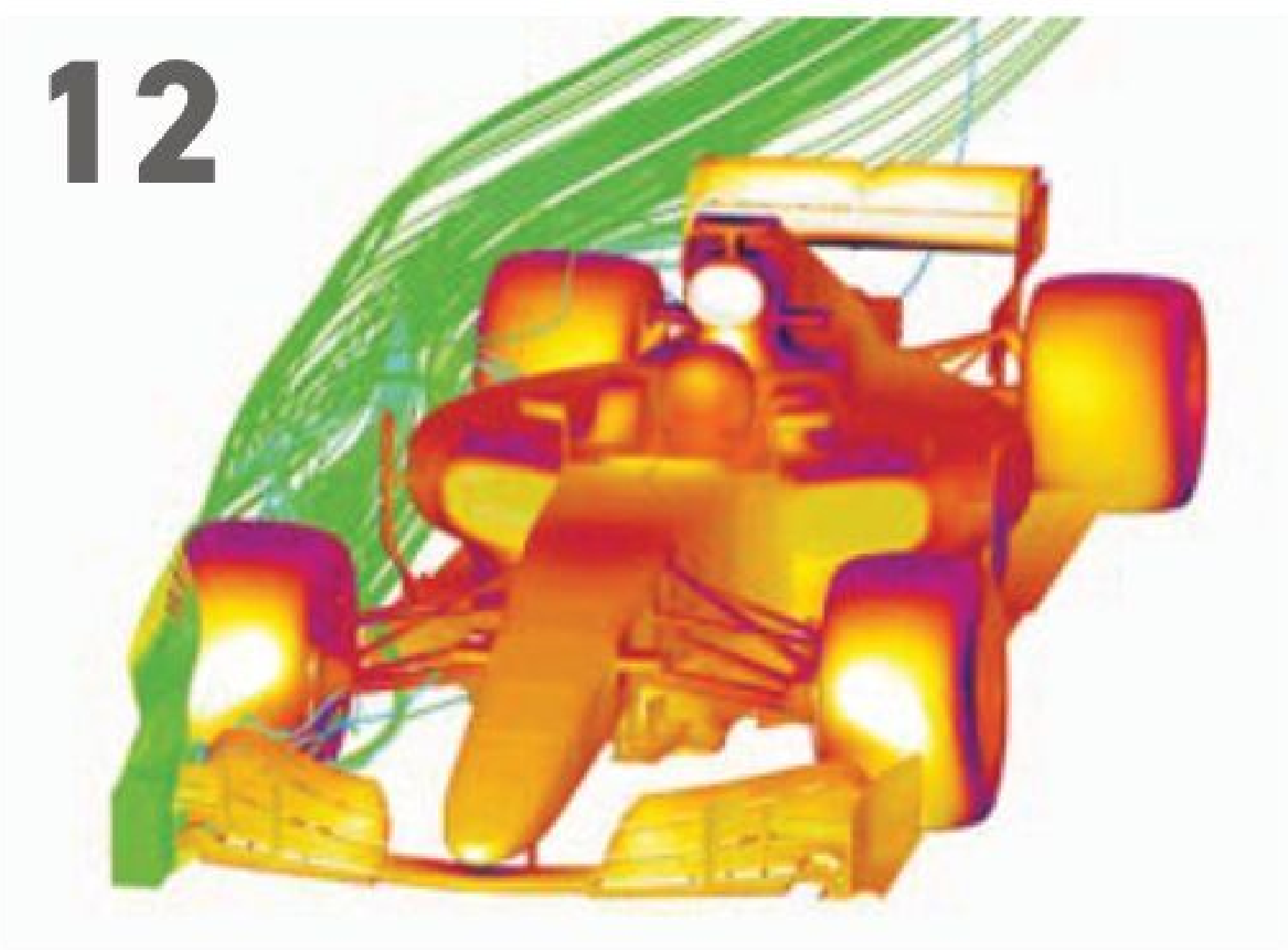
Post
Racecar Engineering,
Subscriptions Department, Sovereign Park,
Lathkill St, Market Harborough,
Leicestershire, LE16 9EF, United Kingdom

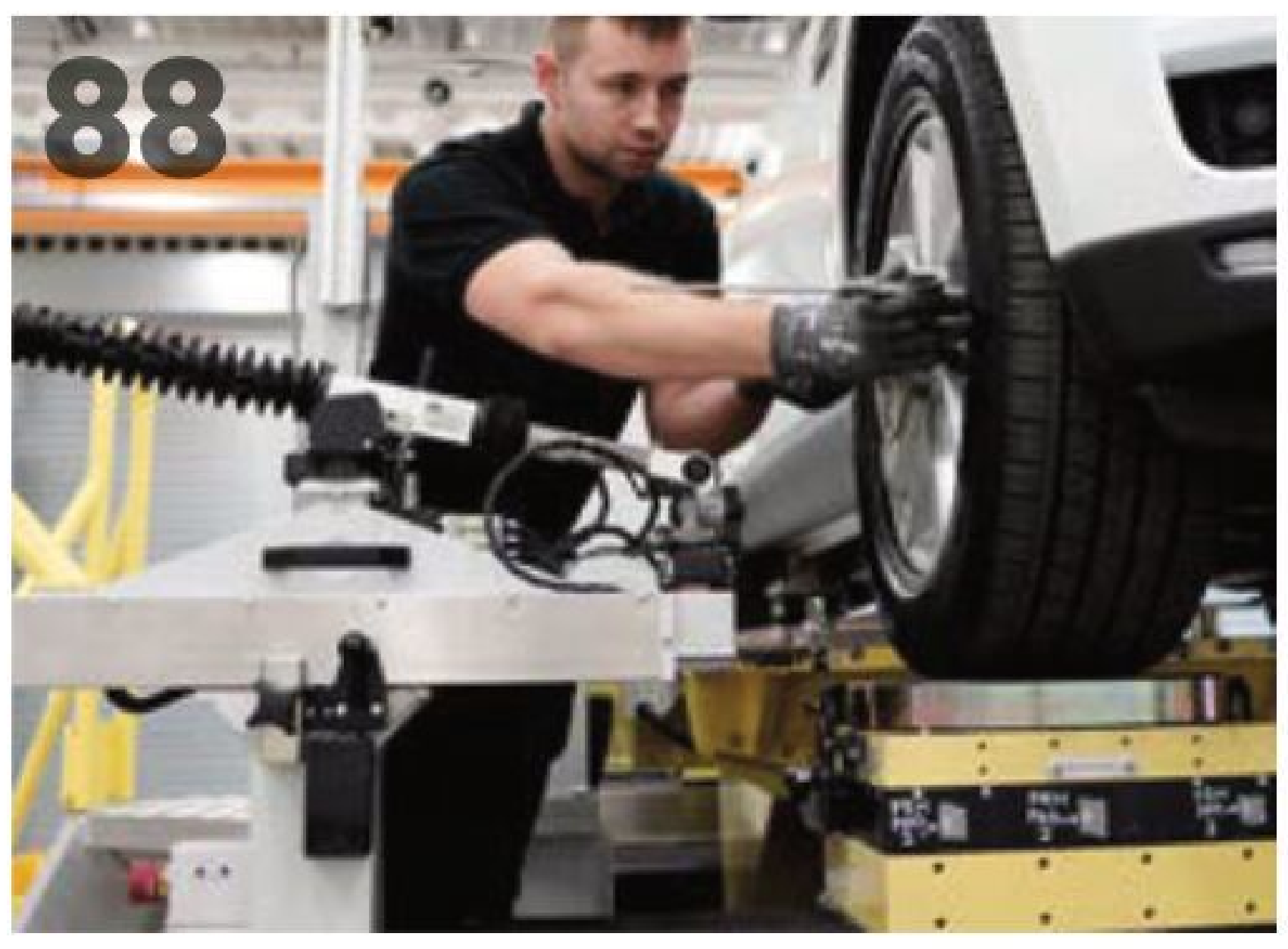
Racecar Engineering Subscription rates
UK (12 issues) £89
ROW (12 issues) £100
racecar@servicehelpline.co.uk

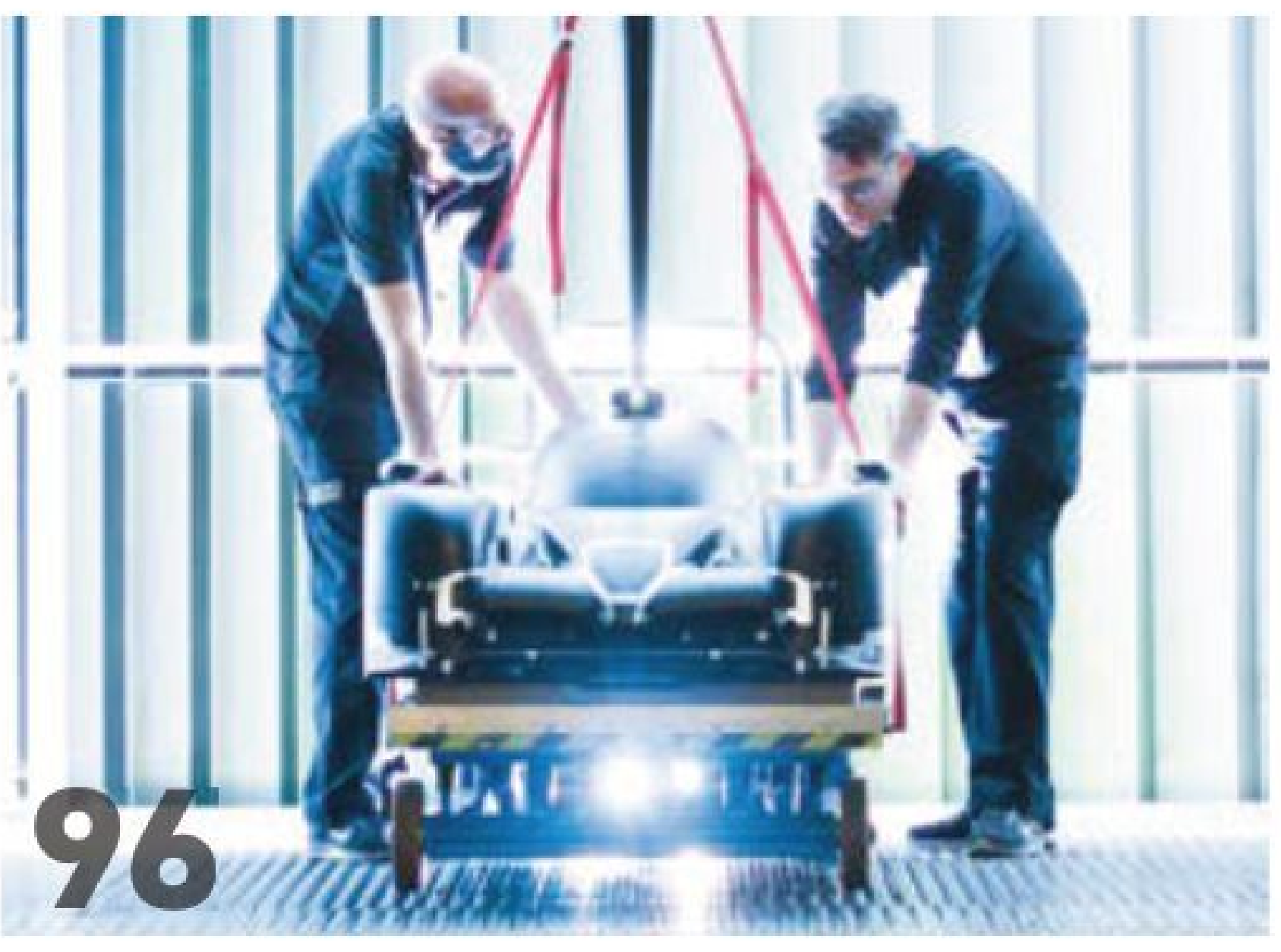
Back issues
www.chelseamagazines.com/shop

News distribution
Seymour International Ltd,
2 East Poultry Avenue,
London EC1A 9PT, United Kingdom
Tel +44 (0) 20 7429 4000
Fax +44 (0) 20 7429 4001
Email info@seymour.co.uk

Printed by William Gibbons
Printed in England
Print ISSN 2634-4939
Online ISSN 2634-4947







INTRODUCTION

RACECAR DESIGN

COMPUTING

MONOCOQUE

ERGONOMICS

COMPUTER AIDED DESIGN

VIRTUAL ENGINEERING

ENGINE TESTING

PRINTING PRACTICES

MACHINING

METROLOGY

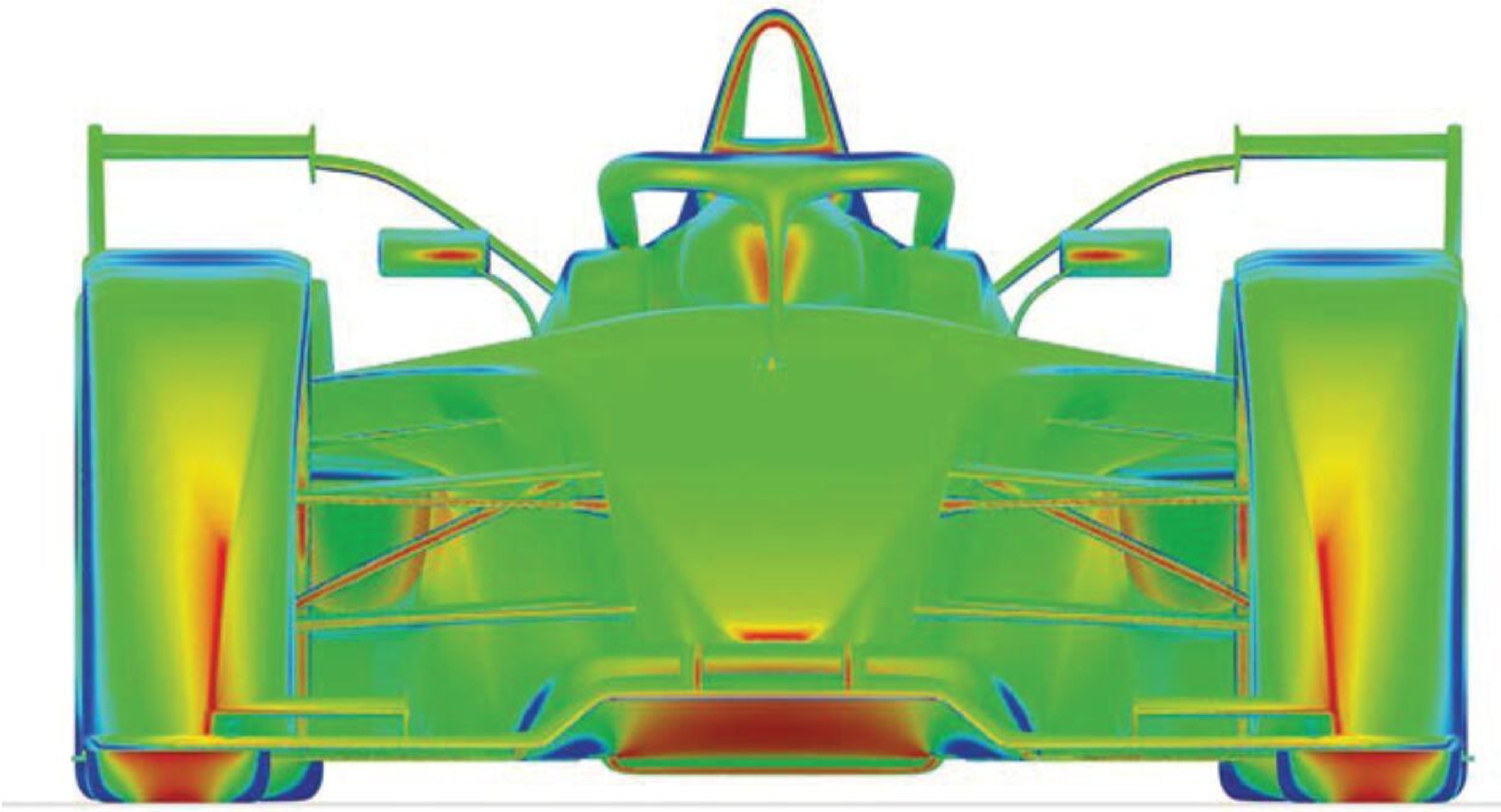
RACECAR SET-UP

DAMPER CONTROL

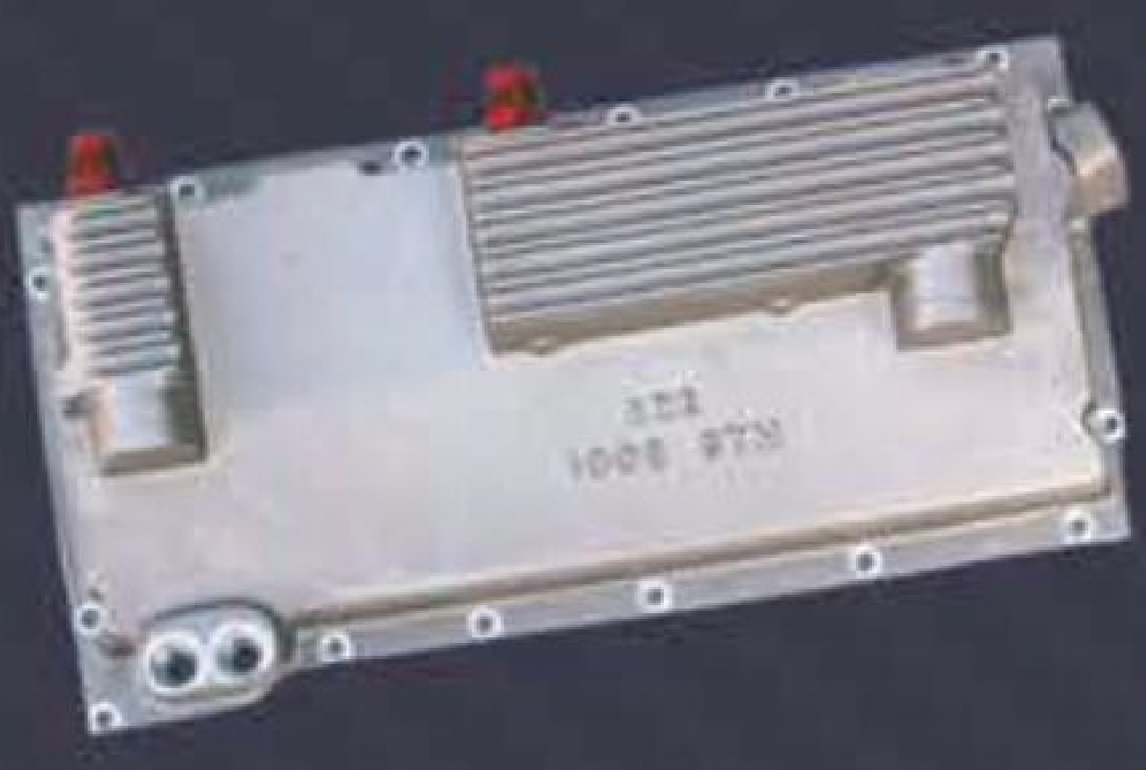
AERODYNAMICS

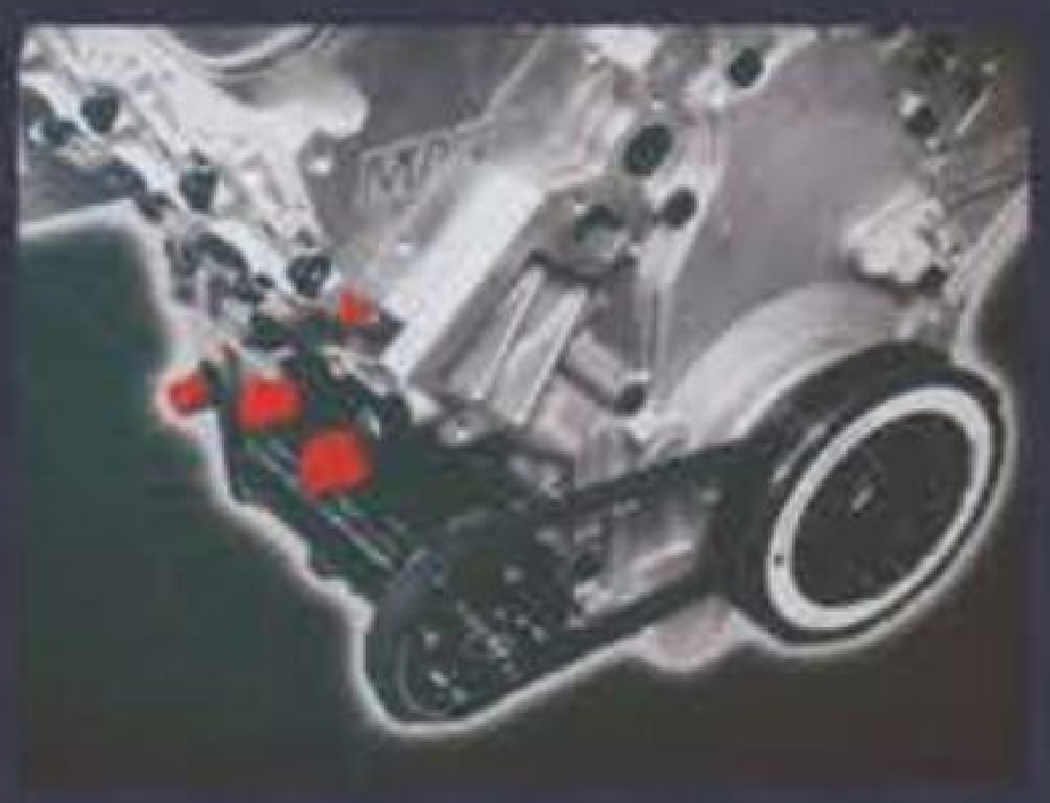
SAFETY

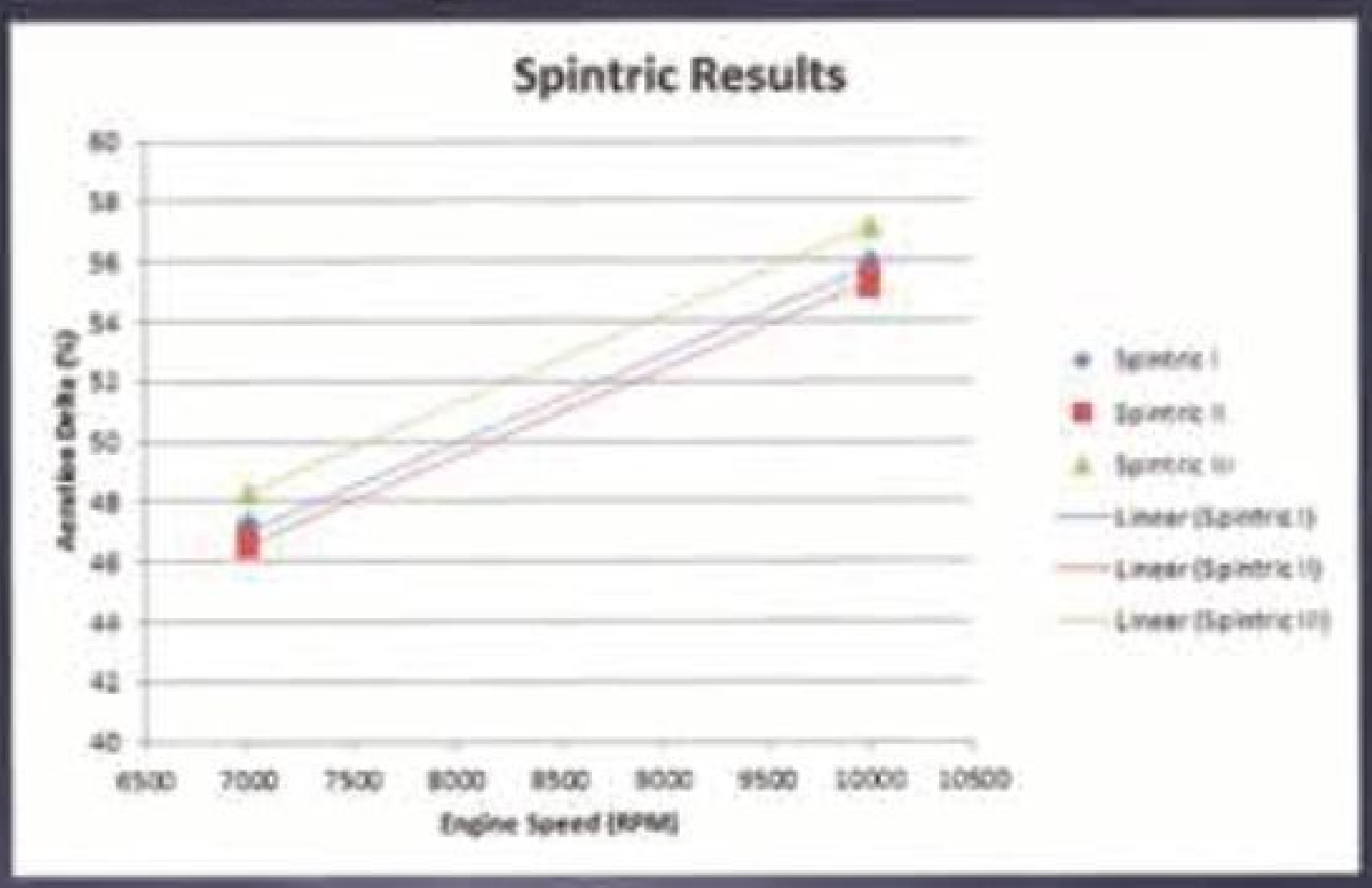
COMMENT



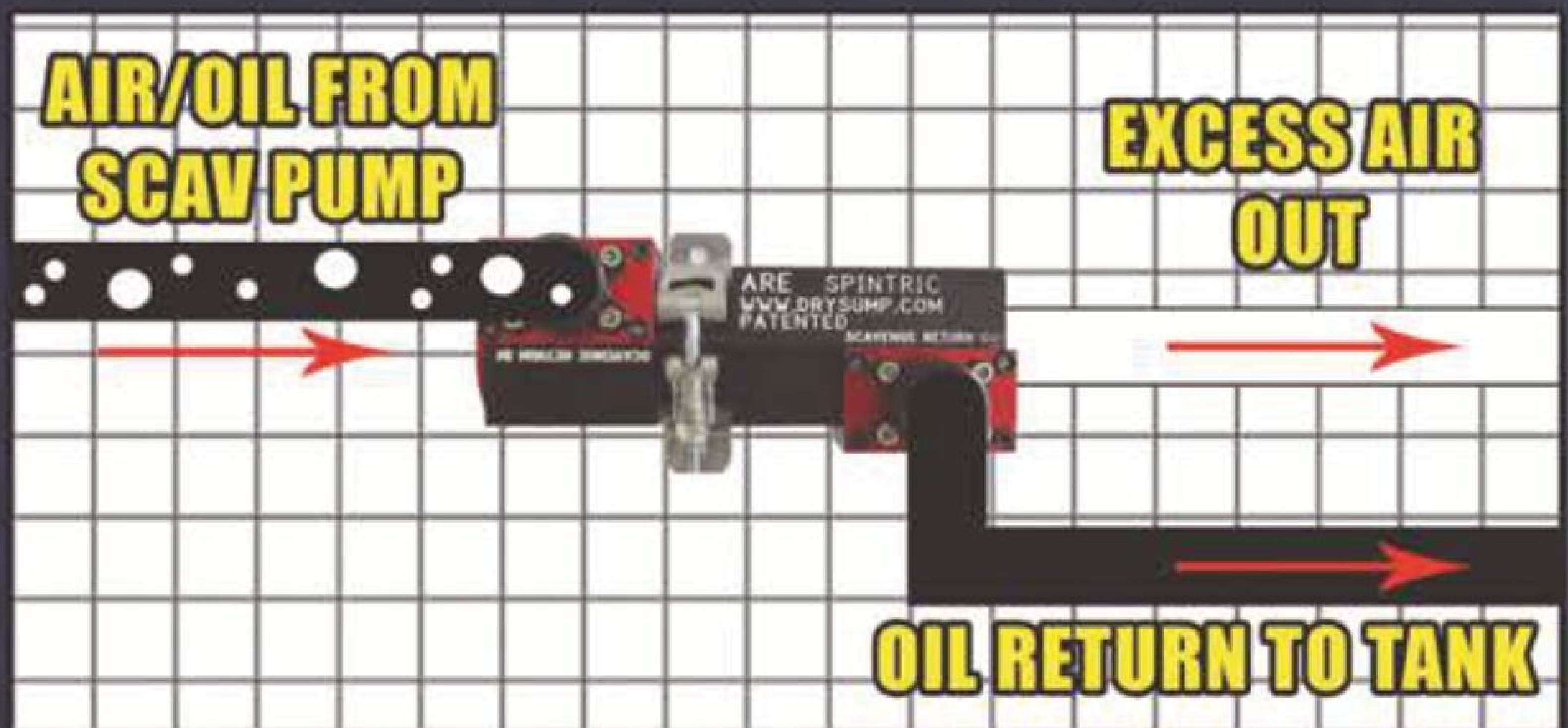
Design of a Racecar is published annually and is a *Racecar Engineering* publication. Although due care has been taken to ensure that the content of this publication is accurate and up-to-date, the publisher can accept no liability for errors and omissions. Unless otherwise stated, this publication has not tested products or services that are described herein, and their inclusion does not imply any form of endorsement. By accepting advertisements in this publication, the publisher does not warrant their accuracy, nor accept responsibility for their contents. The publisher welcomes unsolicited manuscripts and illustrations but can accept no liability for their safe return. *Design of a Racecar* (ISSN 2634-4939/47) is published by Chelsea Magazine Company.







Spintric Results
60
58
56
54
52
50
48
46
44
42
40
Aeration Delta (%)
6500
7000
7500
8000
8500
9000
9500
10000
10500
Engine Speed (RPM)
Spintric I
Spintric II
Spintric III
Linear (Spintric I)
Linear (Spintric II)
Linear (Spintric III)



AIR/OIL FROM SCAV PUMP
EXCESS AIR OUT
OIL RETURN TO TANK
ARE SPINTRIC
WWW.DRYSUMP.COM
PATENTED
SCAVENGE RETURN IN

SPINTRIC.COM
SCAVENGE RET. OUT
SPINTRIC
SCAVENGE RETURN IN
SPINTRIC TECHNOLOGIES

Full speed ahead

The world of racecar design has changed dramatically over the last 40 years, with more tools available to help designers make cars lighter, faster and more efficient than ever before. They are safer, better tested and created with less adverse environmental impact than any time in history, making them probably the most efficient racecars ever produced.

The tools that have made this possible range from the incredible increase in computing power and programming that allows components, and even entire cars, to be created in the virtual world before a single part has been cast, to a range of new materials that have increased strength while reducing weight, and to new build techniques such as rapid prototyping that enable ever more complex structures to be created with less waste material. These processes have quickly become so advanced that they are increasingly being used on the final product, rather than just scale model or prototype design.

New technologies have to be incorporated into the design of a car from the start, with advanced electronics, new materials and aerodynamic devices that are honed in the wind tunnel and with pressure sensors out on track.

Electric energy is becoming an increasingly important part of the design, from the hybrids that race in Formula 1 and at Le Mans to all-electric categories such as Formula E and Rally Raid. Batteries and motors not only require design into the final package but, particularly in the case of Le Mans, occasional four-wheel drive also creates further challenges for a design and development team.

It is not only in the virtual world that testing has changed. In the practical world, the advancement of rigs that help improve suspension design, dynos on which engines can complete full race distances before ever being fitted to a car, and new materials that improve strength and aspects of safety is moving along at speed.

However, even with the new technologies in the design and build phase of a car, the fundamentals remain the same. Weight is still the key enemy of the racecar designer, and reducing that within the regulations, within the boundaries of safety and using the modern technologies that are available is key to success. Cars are built to a minimum weight by regulation, but the lighter the original design, the easier it is to place the ballast necessary to bring the car up to competitive weight, and the placement of that ballast is in itself a performance tool.

> **» Even with the new technologies in the design and build phases of a car, the fundamentals remain the same**

Intelligent interpretation of the regulations, the right designers, with the right tools and correct leadership to develop a car and all its components, plus the application of racing's most famous adage – how fast can you afford to go?

Budgets are increasingly coming under scrutiny too, further adding to the design challenges at every level.

This special edition, brought to you by the team of expert writers and engineers at *Racecar Engineering*, takes you through the entire design process of a car moving from concept through basic layout to reality. On the way we look at the latest technology and tools that are available to the modern designer, from chassis to engine and aerodynamics, and the effect that these tools have on overall design and testing.

Designing a revolution

The process of creating a racecar has moved on from the drawing board and pencil, but coming up with a competitive car is still as skilful as it ever was

By Andrew Cotton

There is much complaining in the modern world about how similar racecars look, with aerodynamics playing such a key role in optimising chassis and bodywork design to the point there is little other than the colour and stickers to differentiate them. It's a far cry from the pre-wind tunnel days when cars were designed according to what the creator considered attractive. That led to individual, and in some cases iconic, designs that have been loved by fans ever since.

Yet the design of the car is primarily about finding the most efficient balance between downforce and drag, while also meeting stringent safety requirements, and therefore time is spent in the design phase trying to find the best of all worlds.

So how do modern racecar designers go about taking a blank sheet of paper and turning it into a race-winning design?

Read the rules

The first step is to look at the championship, and what will be the requirements of the car to compete. For example, Formula 1 allows for open development for all teams. There are some parts that can be shared with the engine supplier but, other than that, the chassis, suspension, gearbox and cooling are all in the hands of the teams' designers, and are vital elements when it comes to designing a car. Formula 1 cars can be evolved mid-season, adapted according to whichever track the cars are racing, and they can be improved throughout the year.

For other categories, particularly endurance racing, a base design may be required to take multiple options for engines, gearboxes and aerodynamic kits, and so must be adaptable. Mid-season development is not possible as the governing bodies try to double-down on expenditure with long periods of stable rules, homologated parts that cannot be

Gone are the days of dirty, oily workshops, racecar construction is now akin to surgery, with computers continually present

Familiar tools are still required, though, and a sound understanding of engineering practice

Pics courtesy Multimatic

The first step in any racecar design project is to look at the regulations for the series you intend to enter and what the requirements are of the car. The rules lay out the basic parameters of the car, including safety requirements and powertrain options. Pic courtesy of Multimatic

developed for performance and restrictions on testing, either in the real or virtual world.

With some series adopting performance balancing, it could be argued that the design of a racecar should not be so critical, and that whatever is brought to the track will be given more or less performance, but the base car has to be right for that to work.

Parallel process

The process of designing a car starts long before pen is put to paper. 'Generally, in most categories we have been involved with recently, you are involved in the regulation process and start designing the car before you have the final version of the regulations,' says David Floury, technical director at ORECA, which provides cars at all levels of endurance prototype racing. 'There is not one stage where you read the regulations, and then another when you design the car. It is all done in parallel.

'Working with the regulations is a continuous process. Every day you re-read them and make sure you understand them, and cross check your understanding of the rules, and cross reference with the FIA and ACO, or whoever, to get clarification to ensure your understanding of the rules is the same as theirs.'

The regulations are where the basic parameters of a car are laid out, including maximum length, width and height. Minimum weight is also set, and in some cases maximum and minimum wheelbase.

» 'There is not one stage where you read the regulations, and then another when you design the car. It is all done in parallel'

David Floury, Technical Director at ORECA

If spec parts must be used, having good lines of communication with suppliers is vital to a smooth running operation

At the heart of the regulations is safety, and so from the start aerodynamic stability is crucial, as is the design of the safety cell in which the driver sits.

'The general starting point has to be what freedoms are allowed to you,' says Julian Sole, chief designer at Multimatic, which has developed cars for sprint racing and endurance, from production-based cars to prototypes competing for overall victory at Le Mans.

'Most of those are based around the safety regulations, and there are some fairly broad topics, such as the fuel cell, which is likely to be behind the driver and not going to wrap around them.'

Building blocks

'You need to get your big blocks in place, so what is the minimum wheelbase and maximum? What is the engine length? Does the championship have multiple engine options? Nowadays, because you have championships with multiple engines, [they] tend to fix a minimum range of volume so you know you are going to have an engine that fits into a hole.

'To start off with, driver position is normally dictated by safety regulations, which means the feet can't be ahead of the centreline of the front wheels. With the wheelbase, you then know the starting point of where the driver will sit. Then you need to know what are the power levels, what race distance are you going to end up with and that pushes the decision on the fuel volume. From there, you know what you are trying to get in the centre of the car.

'That then positions the back of the chassis. Then you need to know the engine volume growth, and then you know what space you have for the gearbox and the amount [of space] needed for the rear axle.'

Once these parameters are laid out and agreed, the designers can start to fine tune their creations. For teams that have the budget and expertise, they can then begin to design and build core components, but many teams will rely on external suppliers for items such as the composite work, suspension, brakes and radiators. Some are able to specify to their partner teams the design and have it built bespoke for them, others have to adapt their design to available parts.

'Everything is decided at the design stage and you carry different subjects in parallel to move forwards, taking in different aspects at the same time,' explains Floury. 'That means general vehicle architecture, weight distribution, aero concepts and structural analysis. You work all of this in parallel because if you only work on the aero you might end up in a corner in another area of the car.

'You have to have a global picture of your car, and clearly you involve some technical partners early on. Tyres are a central element as they drive a lot of your targets for the car in terms of weight distribution and aero balance.'

While everything above the centre line of the wheels is pretty much fixed, the tyres degrade more than any other part of the car, and sometimes the ability to keep them working for longer can be the difference between winning and losing a race.

'The championship will normally dictate the tyre size, and that part of the regulation is done in consultation with the tyre suppliers,' confirms Sole. 'It's a regulation thing, but it would be done with input from us and the tyre people as to where we want to go with tyre sizes, and then that gives you the weight distribution based on that.'

Shapes of things

While Formula 1 designers are able to design around a single athlete, LMP designers, and designers of spec cars for F3 or IndyCar, have to design for multiple body shapes and sizes, often for drivers with differing heights and weights. Flexibility is the key here, as is all-round visibility.

'The footbox height and driver ergonomics are all regulated,' says Sole. 'There is always a volume for your feet, and you can't lift that too high because otherwise the driver can't see where they are going. Now [in LMP design] we have vision templates so you can't lift the footbox up further than a set height.'

In turn, the height of the front of the car has a direct impact on the front suspension, which has to be mounted to the tub. 'From the overhang of the bodywork and what length that gives you for a front crash structure usually drives a lot in that area,' says Sole. 'Where you fit the front suspension in there's usually an interesting design loop. In terms of aero, your flow coming off the front splitter around the lower wishbone, there is always something there to consider in terms of what you are tuning and how you position that. They are generally fighting for space.'

Stress management

One of the key areas of development is the engine, and even here there are multiple different approaches that are needed. For some, the engine is stressed and carries some of the load at the mid-section of the car. Others are housed in a cradle, non-stressed, which generally is heavier and less rigid, but cheaper to make.

Very few teams or manufacturers are able to produce engines to their own specifications. That is almost exclusively the preserve of the manufacturers, while commercial engine builders build to order. 'You have to draw your big engine and small engine that is going to come along at some point, versus an inline engine always has a different footprint on the back of the tub and the load paths are quite different,' says Sole.

'Some of the projects, like LMP2, the engine is fixed by regulation, so it is coming very early in the project,' adds Floury.

> **» 'Tyres are a central element as they drive a lot of your targets for the car in terms of weight distribution and aero balance'**
>
> David Floury, Technical Director at ORECA

The LMP2 category has used the standard Gibson engine since 2017 in all forms of competition, save for the US where the engine comes from a manufacturer that can then have a styling influence over the aerodynamics. That, then, is balanced to negate the effect, positive or negative, on aero efficiency.

'If are doing a factory LMP1 car, obviously the engine is central to the concept, so you design the car and the engine together as one,' Floury continues. 'If you design an LMDh car [for US competition], at the stage that you design the survival cell, you might not know all the engines that you have to integrate because you might have OEM manufacturers joining in two years' time once your chassis is designed and homologated. You then have to have flexibility and more room to accommodate the different architecture.'

Adding in different lengths and weights of the engine also adds to the complexity for the teams.

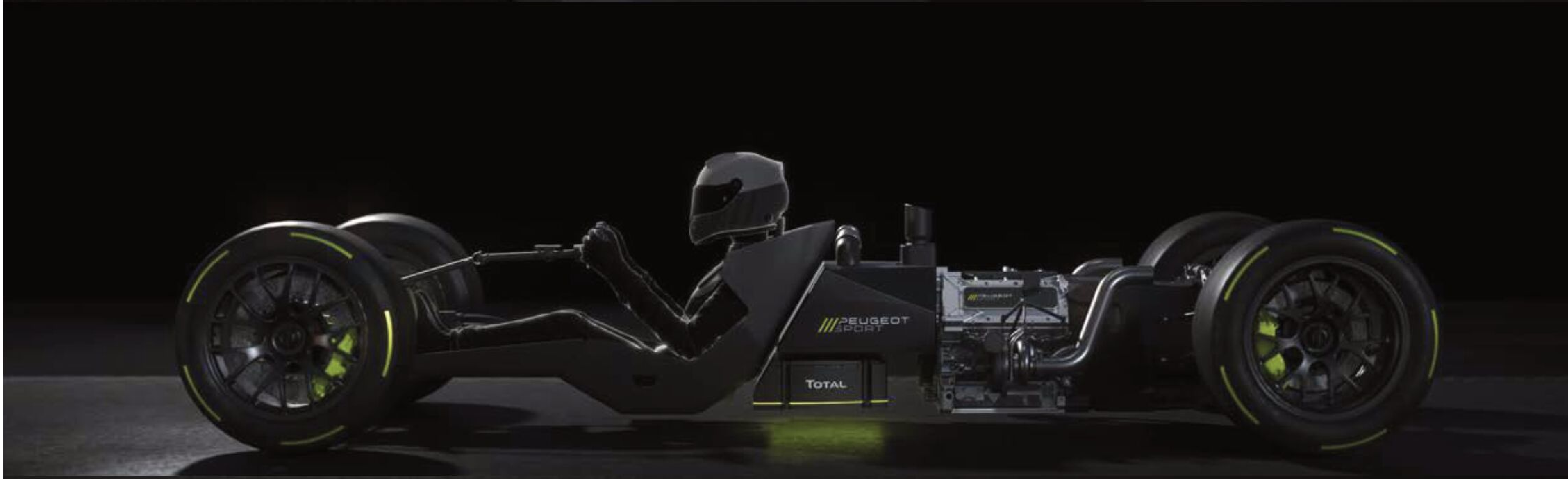
'The car could have been designed for two years when another engine comes along that is a high boost and needs a lot of intercooling and water cooling,' says Sole. 'It needs a quantity of water and oil, so you get some fairly big packaging challenges when you already have a bodywork design.

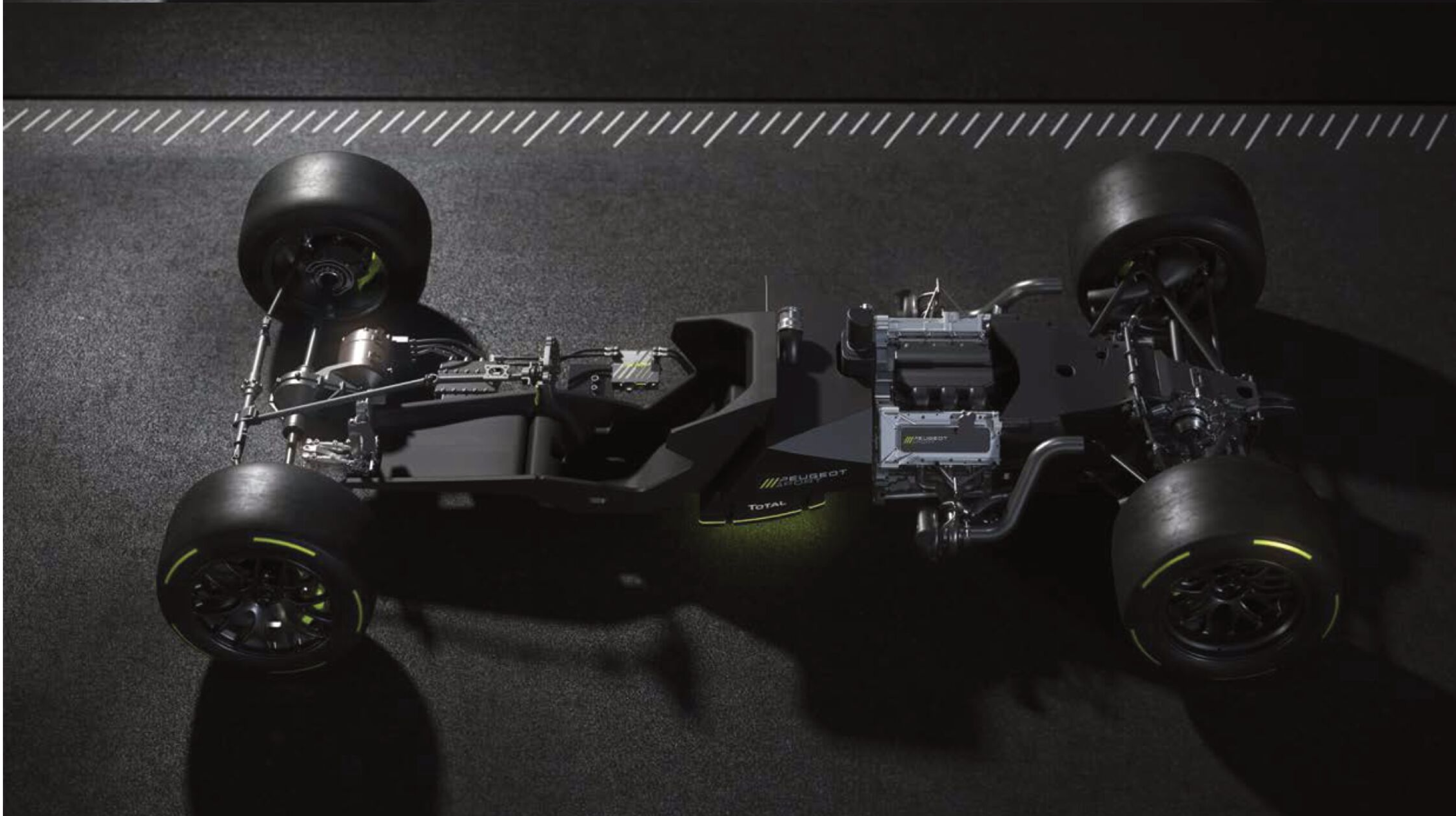
'When designing the chassis, you know that at some point you will get a turbo variation, so there's no point in just designing for a simple, normally-aspirated engine and expecting the cooling system will be good for everything. Sometimes trying to fit a cooling system that's way bigger than you have space for, you have to get inventive, with additional air intakes around the car to feed the additional coolers.'

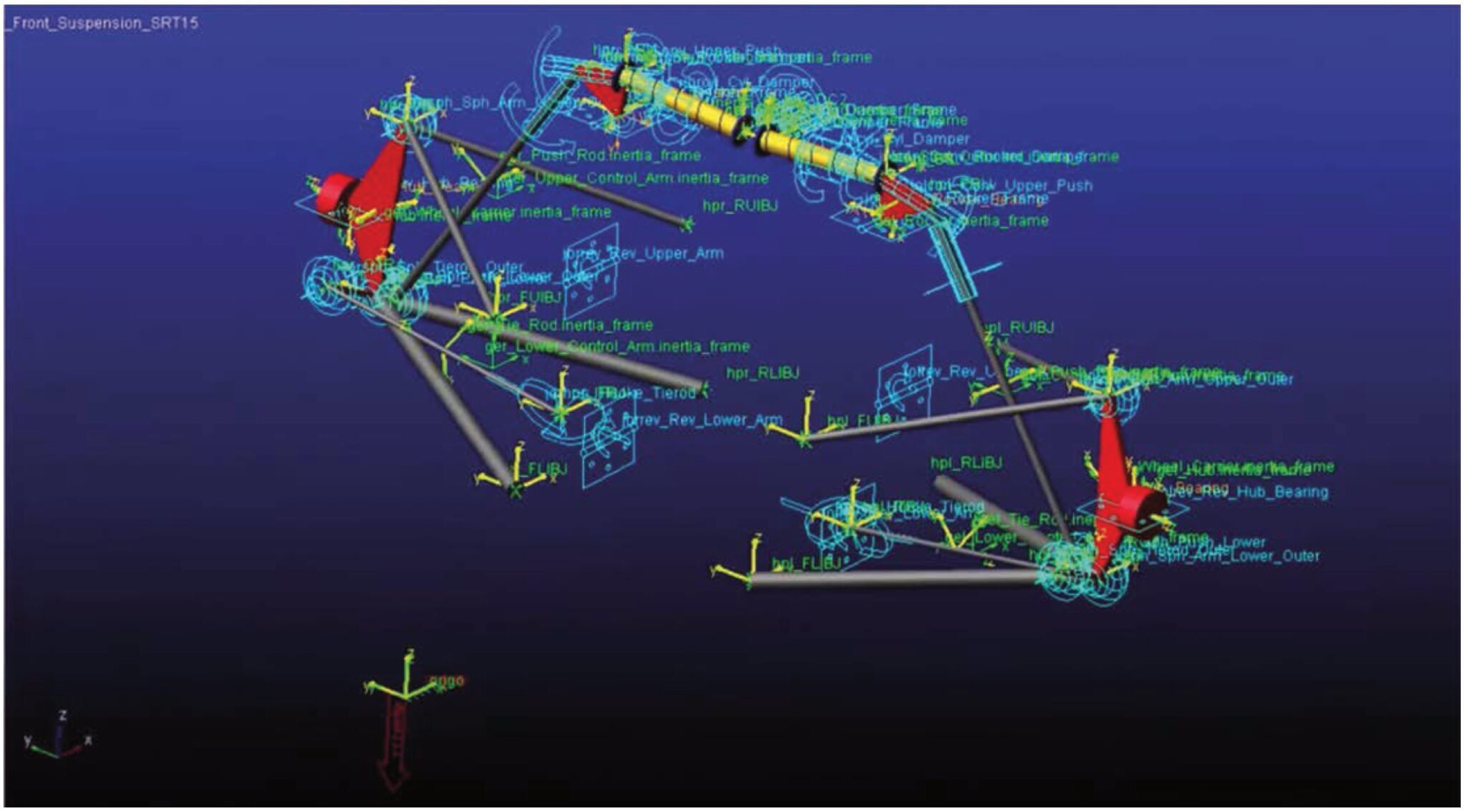
With the weight distribution, powertrain including the gearbox and suspension layout all diverging onto a design, the aerodynamics also play an incredibly important part in the overall design. Efficient aero delivers on top speed, downforce and drag numbers,

Right: Designers treat racecars as a series of building blocks, with specific volumes. Once the main ones are known, along with the safety regulations, driver position can be determined, though feet will always be positioned behind the front wheel centre line

Pics courtesy Peugeot


PEUGEOT SPORT
TOTAL


PEUGEOT SPORT
TOTAL



Universita del Salento

At every stage parts and designs are tested and validated on the computer. This digital model of an axle contains all the physical information required to perform a compliance study

all while also creating airflow to key components for cooling, and packaging.

'In the last 20-25 years in Formula 1, the front suspension layout is really aero-driven,' says Floury. 'If you were to design an F1 car without aero, and purely design it towards suspension, you will probably not end up with what you see in F1 currently.

'At the end of the day, you have to understand where you can extract the performance and, when you are designing to a cost target, you have to understand where the performance efficiency is.

'Basically, if a tenth of a second is 100,000 Euro, what is the ratio between the lap time and the costs involved? You then prioritise what you are doing.'

Critical advantage

While accommodating the needs of the various departments, with the engine department looking for cooling, the aero department looking for a clean surface and the mechanical engineering looking for space in which to house key components such as the suspension and steering, a designer also has to keep in mind the fact that this is a competition prototype. The margin between the front of the grid and the rear is so small that any advantage that can be created is absolutely critical.

'You have to assess the risk level you want to take,' expands Floury. 'That can mean the risk level in terms of the interpretation you make of the regulations. It can be in terms of reliability, or in terms of a design concept that is new. Have I tried to simulate it, and am not sure that it will work as I think it should? You need someone to have the overview over what you are doing and sometimes closing some doors, even though that is painful to do.'

A feature of modern customer-based racing is that homologation periods are long, allowing a customer to buy a car and run it for several years to maximise the time they are able to compete without a large outlay in new machinery. It also makes it easier when a team is familiar with a car in terms of servicing, particularly in the heat of battle during a race. Yet, teams do want updates as they also want to go faster and, while in many cases designers are not allowed to design performance updates, they are able to improve reliability.

'Obviously, at the start of a project you have very high progress rate, and then it slows down, but you *never* find a place where you spend time and energy and don't gain anything!' says Floury. 'The efficiency drops through the development, but you keep making progress.

'When you are not allowed to develop the car, or develop the performance, as is the case with LMP2 during the homologation cycle, you have time to sort out issues such as when a project you are using is not manufactured anymore, or you have reliability issues.

'Obviously, in Formula 1 this is not the case, as cars at the start of the season in Australia are clearly not the same as the ones that finishes the season. It is a continuous development throughout the season.'

Designing for change

In IndyCar, for example, the basic chassis from Dallara has remained unchanged since 2012. Since then, though, it has had to manage different aero packages from Honda and Chevrolet, and in 2020 introduced the revolutionary Aeroscreen head protection device that not only had to be capable of withstanding incredible forces, but also fit securely to a cockpit surface never designed to accept it.

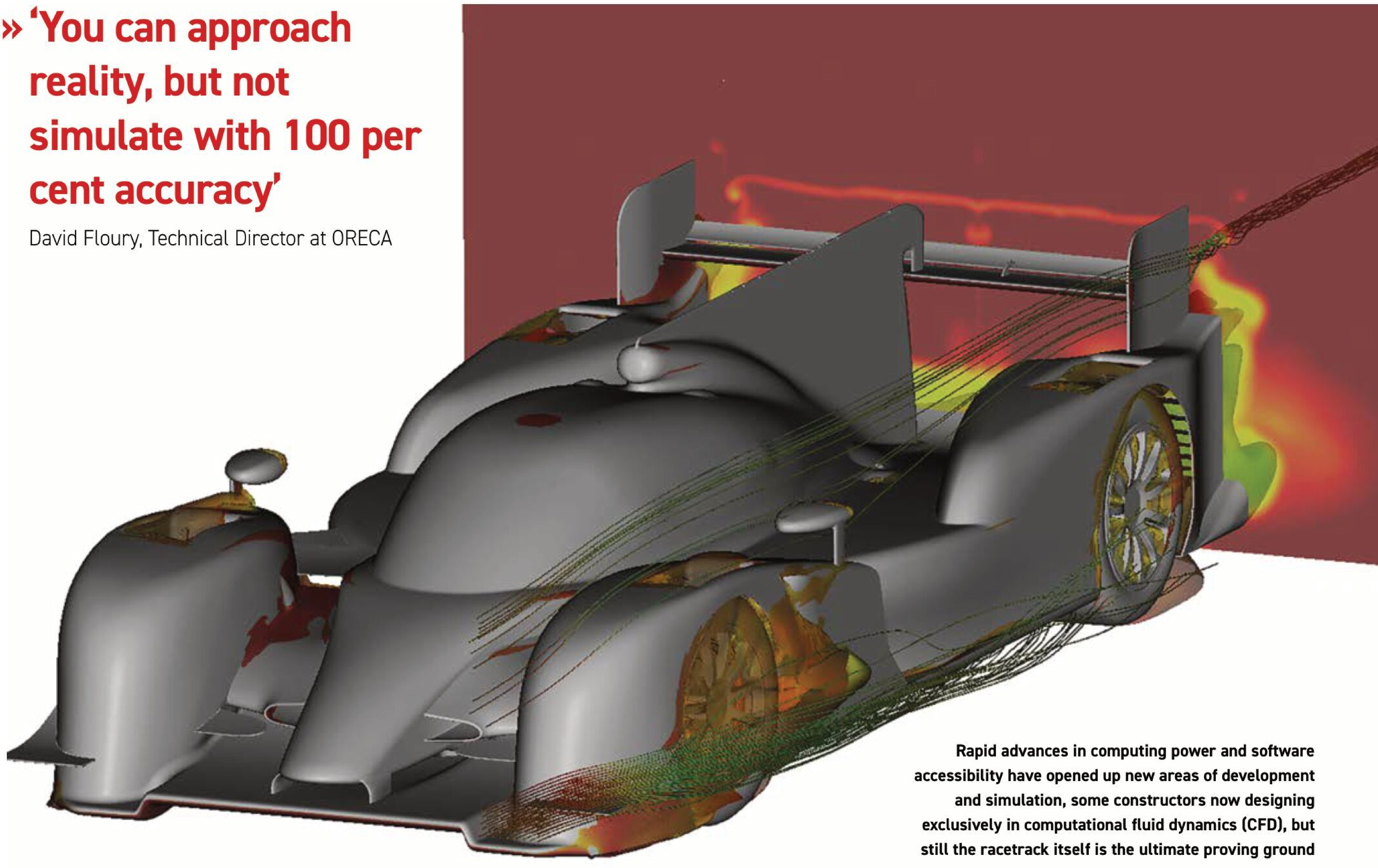
> » **'The design period is never based on the tools we have got, it's based on when a customer comes along and says they want a car to be on the track. It is never long enough'**
>
> Julian Sole, chief designer at Multimatic

New engines will require new cooling requirements, and basic safety has moved on since the DW-12 was introduced, but the chassis has been adaptable enough to see the series through an incredible period of change.

Legendary Formula 1 designer, Adrian Newey, is famous for using a drawing board, as he has always done, but his designs are then checked by computer modelling before they are put into production. This not only saves time, and produces more complex parts, it reduces the pile of waste material that has been piling up in bins outside wind tunnels for generations.

» **‘You can approach reality, but not simulate with 100 per cent accuracy’**

David Floury, Technical Director at ORECA



Rapid advances in computing power and software accessibility have opened up new areas of development and simulation, some constructors now designing exclusively in computational fluid dynamics (CFD), but still the racetrack itself is the ultimate proving ground

‘The design period is never based on the tools we have got,’ says Sole. ‘It’s based on when a customer comes along and says they want a car to be on the track. It is never long enough so, no matter what tools you are using, I don’t think you could ever say it has been short circuited, but the computer packages do give you more confidence in your design.

‘When you have finally built the part, you know from the simulators [that it will be effective]. With the suspension design, we have a lot more confidence in general load cases, suspension load, the effect of compliance and kinematic behaviour. You know when you do get to the track that you have something you know where it’s going to be, whereas before that really was day one, really.

‘With engine modelling, they give us some fairly good heat rejection numbers, which is always a benefit because before we would always wait for the first run on the dyno to get those, and even then it was a guess. Now you get more information earlier in the process, which gives you the confidence in your design.’

» **‘Tyres are difficult to simulate in all aspects and in all conditions. The track is changing all the time.’**

David Floury, Technical Director at ORECA

3D revolution

ORECA’s cars have, for more than 10 years now, been designed exclusively in CFD prior to build. Parts are able to undergo Finite Element Analysis (FEA) on computer before build and rapid prototyping, with no need to develop in the wind tunnel. 3D printing has revolutionised the capability of part design. Where before billet aluminium had to be cut away, with the limitations that induced, parts can now be built from the ground up to be extremely light, strong and fit for purpose.

‘At the end of the day, the pencil and drawing board is still a tool and you have to know how to use it,’ says Floury. ‘The tool doesn’t necessarily bring the ideas. It is really cool what it allows us to do, but still it is team work and you have to have vision and ideas.

‘Computing certainly helps with the design as it opens up new areas for development, and for sure we are not at the end of this process. When you see what you can do now with rapid prototyping, it starts to change and will develop in the future the complete approach to designing a part. You can do complex parts, you can optimise the structure of a part, save more weight because you can do complex geometries that were impossible to achieve through machining or casting, or even fabrication. You could not achieve then what you are able to achieve now with rapid prototyping.’

Modern racecar design now allows for 3D printed parts to be on the finished product, rather than just in the scale models, but there is still a long way to go in the development of the tools available to the modern designer.

Even though tyre design and capability are critical to car performance, it is not yet possible to simulate all the parameters needed to create an accurate design in modelling alone. Tyre companies provide the base information, but it is up to the teams to design a car to manage the rubber, and ensure that the vehicle doesn't wear it too quickly.

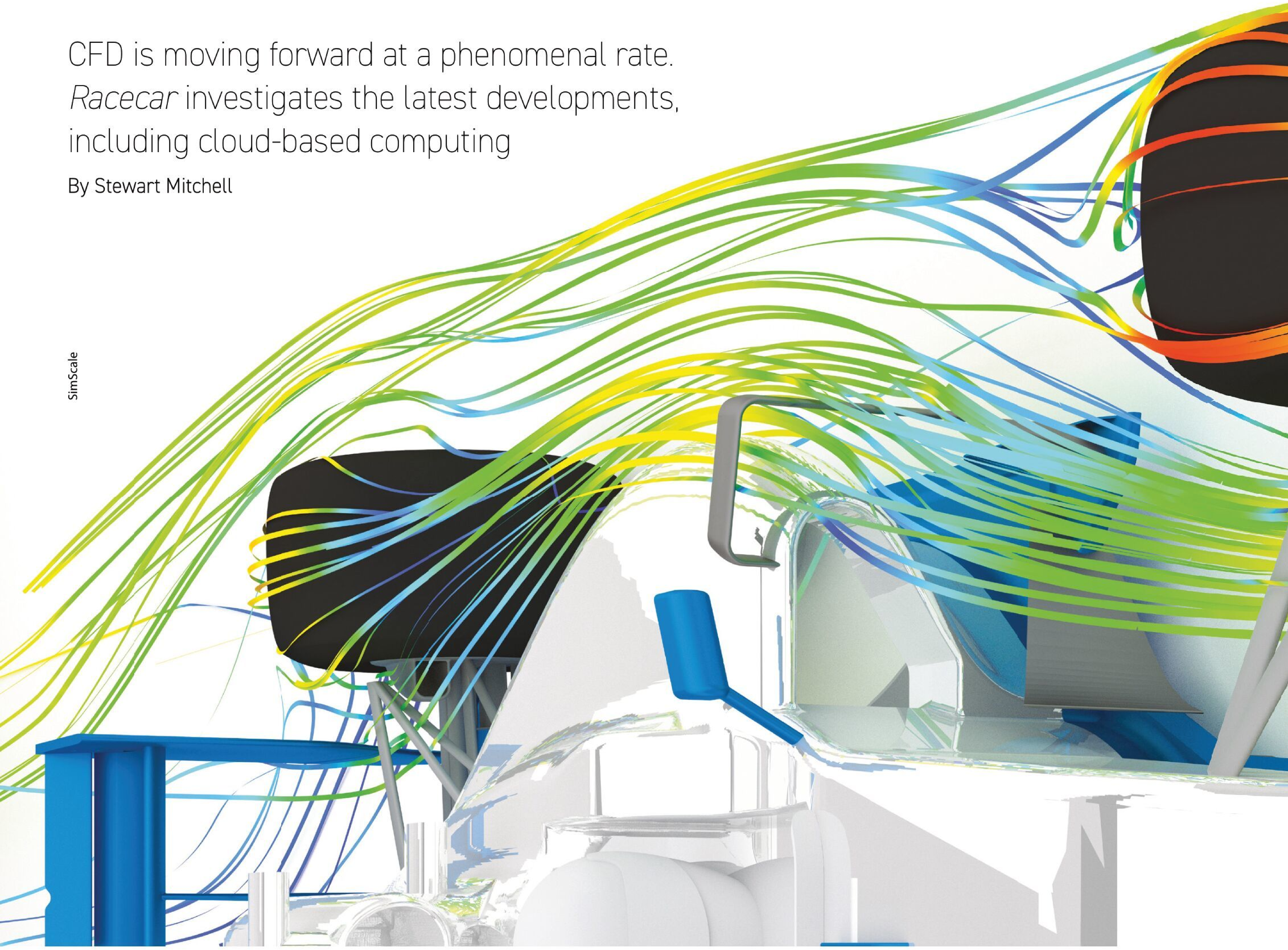
‘Maybe in the future you can do tyre development in the virtual world [but now] it is not realistic to think this,’ says Floury. ‘You still have a lot of things that cannot really be modelled in the virtual world. If you want to simulate all the conditions that the car can be run at in real life at a race track, for example Le Mans, it is very tricky to build these models because the tyres are difficult to simulate in all aspects and all conditions. The track is changing all the time too, with the temperature, with rubbering down and with dust.

‘You enter into something that is very complex. You can approach reality, but not simulate with 100 per cent accuracy.’

Head in the clouds

CFD is moving forward at a phenomenal rate. *Racecar* investigates the latest developments, including cloud-based computing

By Stewart Mitchell


SimScale

Computational fluid dynamics (CFD) is a powerful numerical tool widely used to simulate many processes in the racecar environment. Recent progression in computing efficacy, coupled with a reduction in the cost of CFD software packages and the advent of cloud-based CFD operation, has advanced CFD as a viable tool to provide effective and efficient investigations for the full spectrum of motorsport.

In this article we will discuss the fundamentals involved in developing a CFD solution and provide a state-of-the-art insight into various CFD developments applicable to the motorsport industry, as well as illustrate some of the physical models most commonly used in these applications.

CFD is a computer investigation into fluid dynamics. Personal computers can run CFD for moderate problems. However, the higher echelons of motorsport use clusters with up to thousands of cores and terabytes of memory as the complexity of the flow fields are immense.

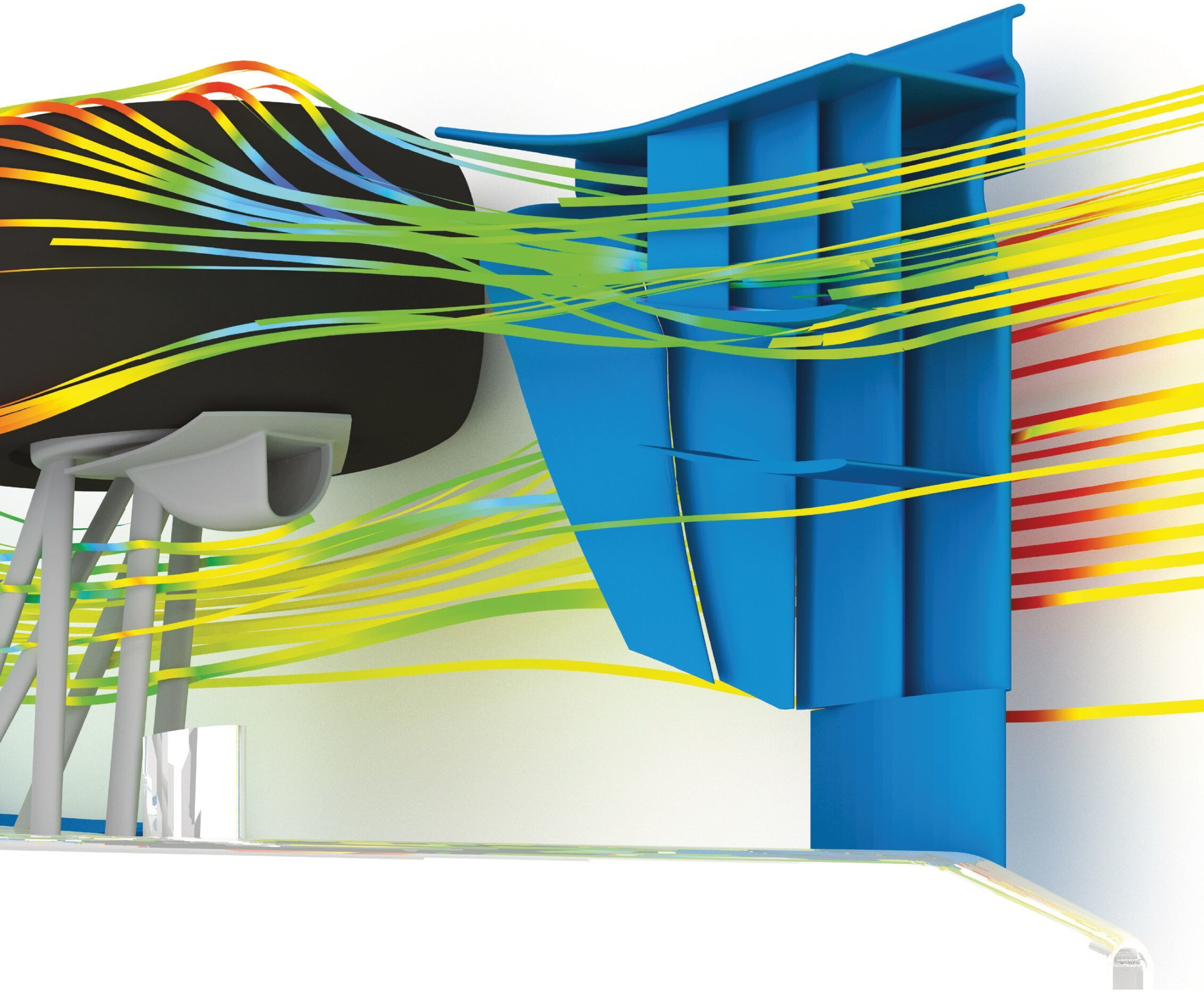
The fluids under investigation can be either a gas or a liquid. When you're working with water, it's called hydrodynamics, and when you're working with air, it's called aerodynamics. The dynamics element refers to the fact the fluid is in motion, which can be caused by an object moving through them, or a thermal effect driving the flow.

Method man

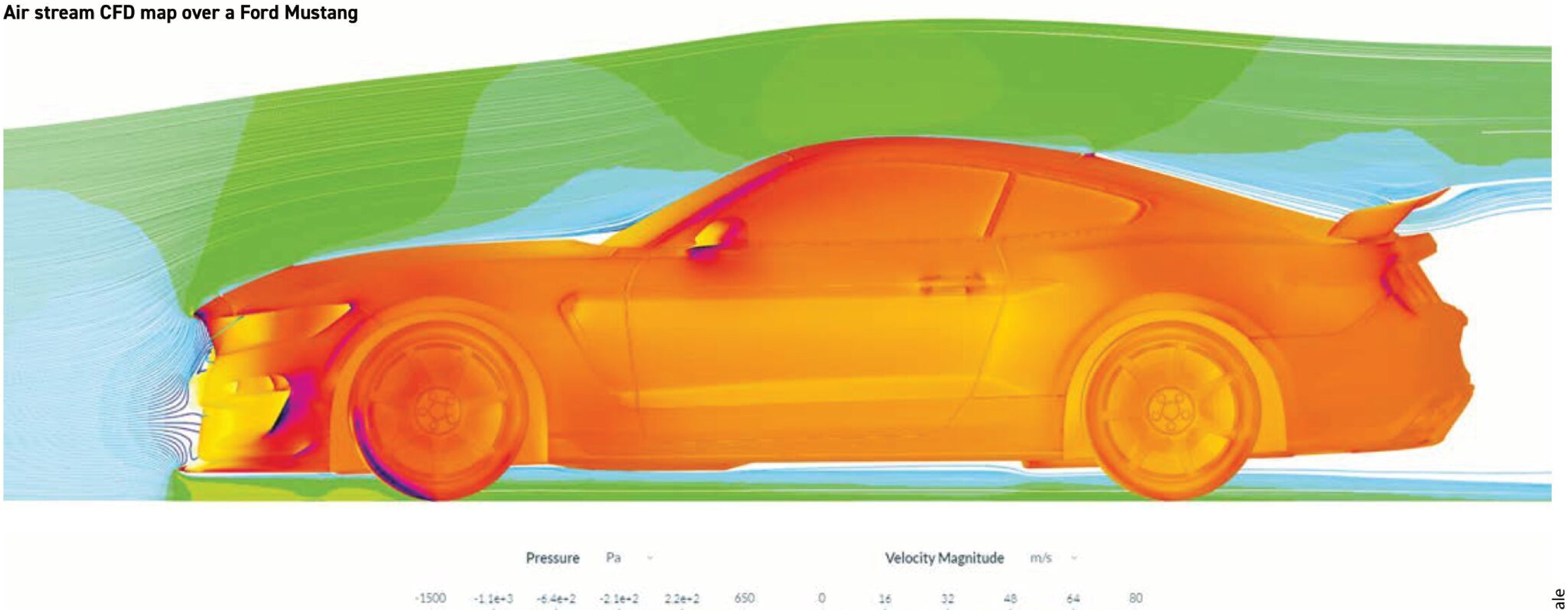
There are three main steps to the CFD process – modelling, discretisation and iteration. Modelling involves the continuous mathematical functions you use to describe the real flow. In reality, that flow is the result of many different laws of physics working together. As CFD is a tool, *you* must tell it how you want it to work.

» 'If you're calculating the aerodynamic force on a wing, for example, there's little use in taking the gravitational pull of the moon into account'

Wouter Remmerie, founder of AirShaper

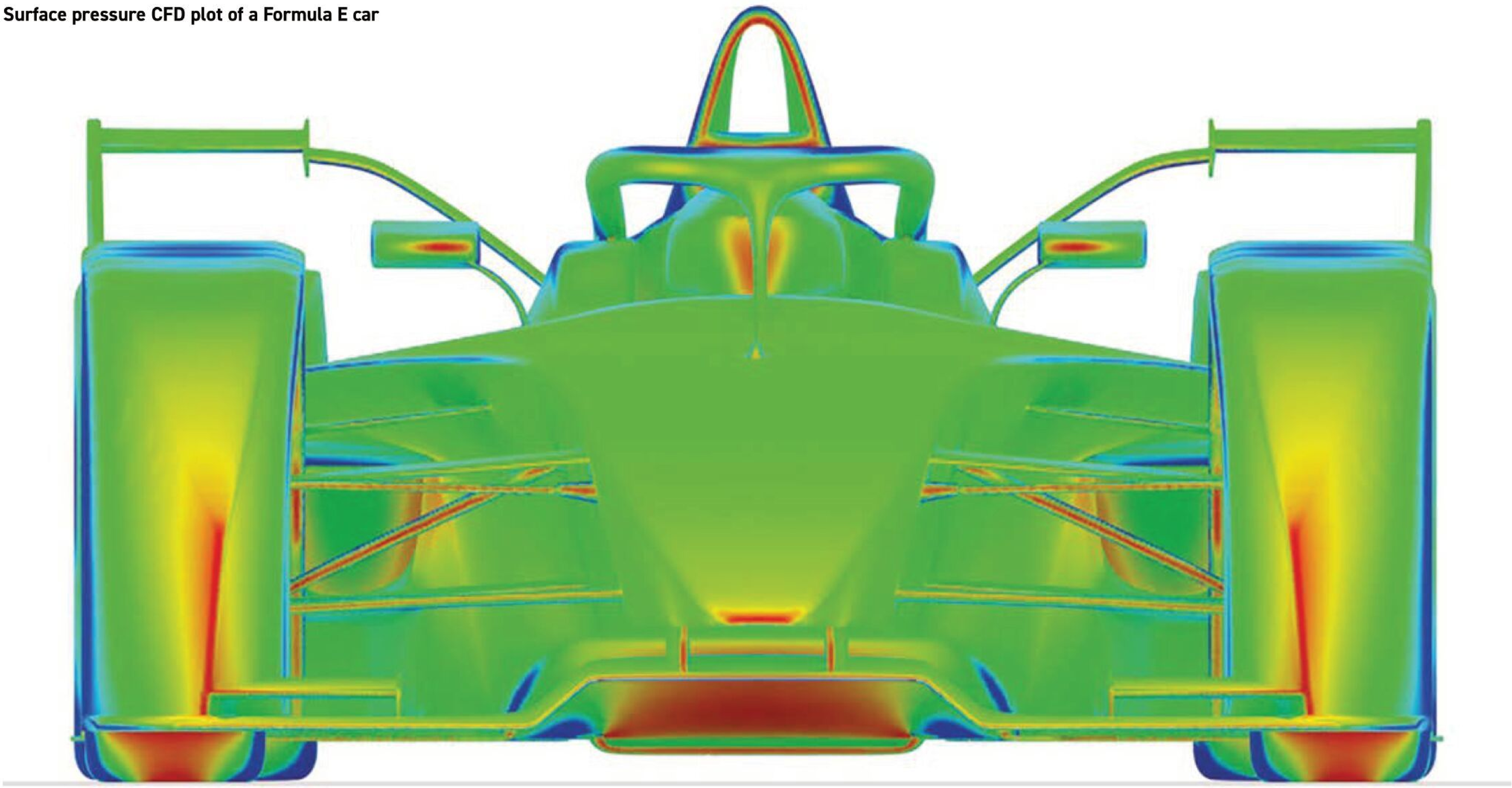


Air stream CFD map over a Ford Mustang



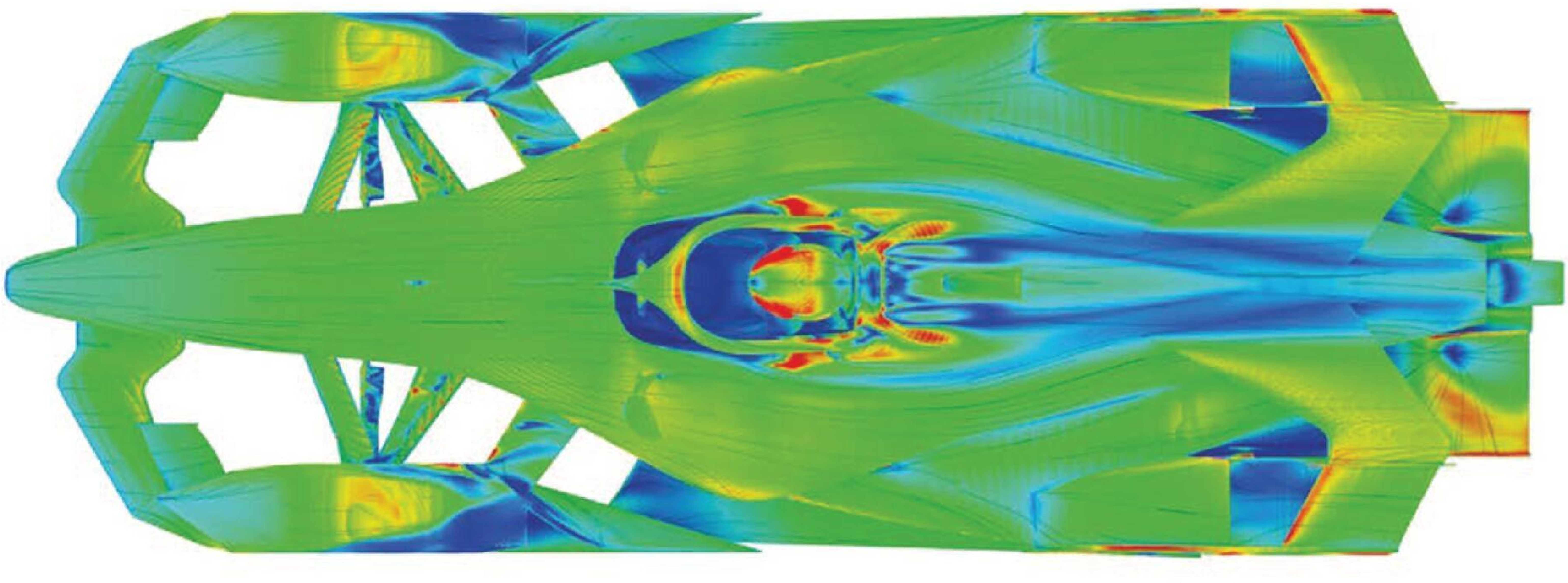
SimScale

Surface pressure CFD plot of a Formula E car



AirShaper

Top plane view of a surface friction CFD plot of a Formula E car



AirShaper

Wouter Remmerie, founder of AirShaper, explains: 'To focus the investigation, it's a matter of selecting only the areas of a study that have a substantial impact on your flow topic. If you're calculating the aerodynamic force on a wing, for example, there's little use in taking the gravitational pull of the moon into account, as the effect is negligible. So, defining correct and relevant models is important to limit the modelling errors.'

Differential equations

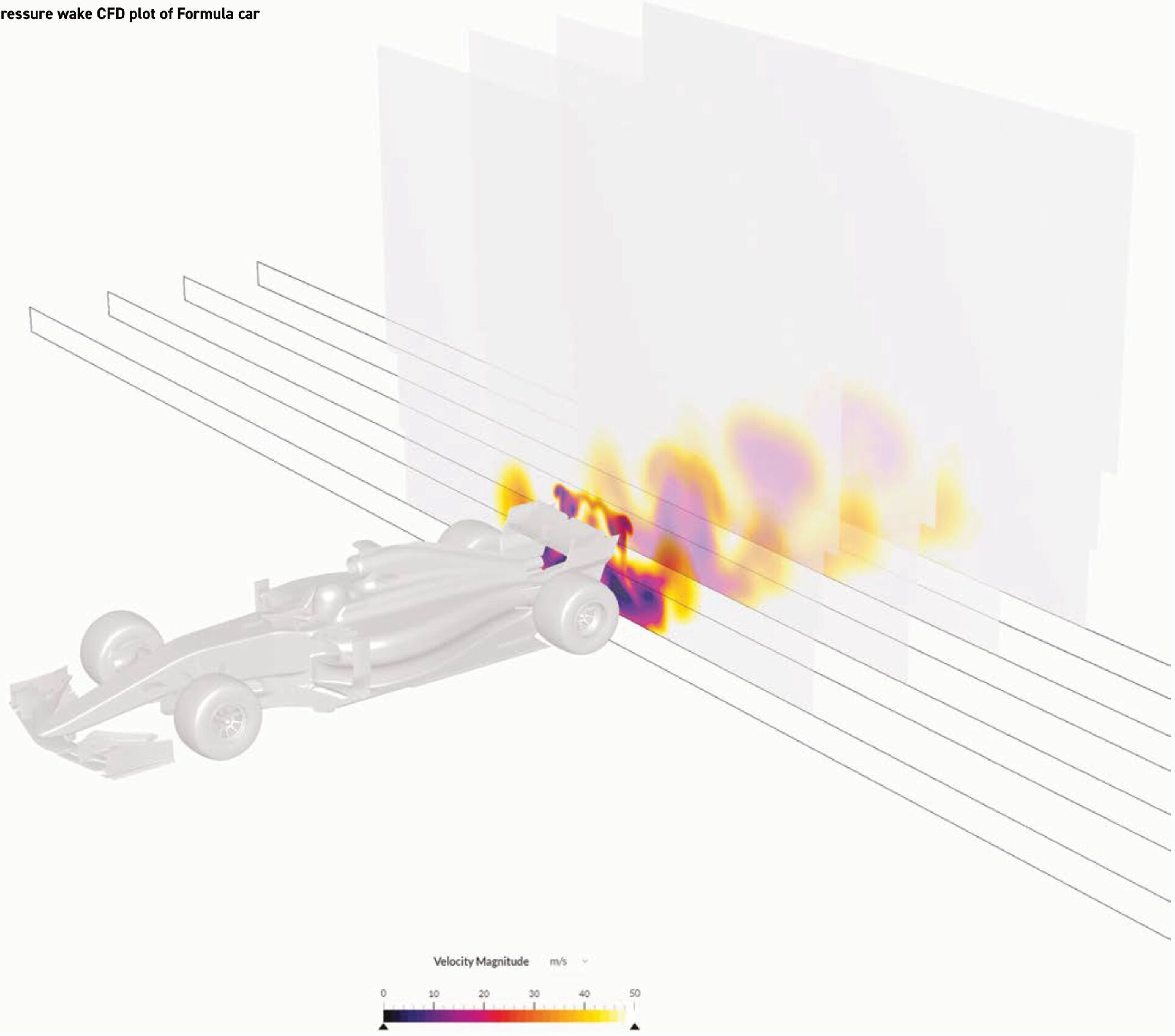
In the case of fluid mechanics, the essential model is a set of partial differential equations called the Navier-Stokes equations. These apply the laws of Newton to each fluid element, stating the dynamic balance between the forces acting on it and the change in its momentum. This conservation of momentum, together with the conservation of mass, allows you to describe the flow field.

'For some straightforward cases, like laminar flow through a pipe, there are analytical solutions. One can describe the entire flow field using continuous mathematical functions,' continues Remmerie. 'These allow you to calculate exact velocity and pressure for any given location in the flow field at an infinite resolution. However, for anything more complex, there is no such analytical solution. That means we need to break down reality into small blocks for which we *do* have a solution.'

These blocks can be finite elements or volumes, known as cells. The process of

» **High-density meshes typically contain millions of cells, and this quickly becomes very computationally expensive**

Air pressure wake CFD plot of Formula car



SimScale

breaking down a large continuous flow field into cells is called meshing. For each cell in a mesh, we can approximate the continuous Navier-Stokes equations by discrete algebraic equations. These allow us to calculate the pressure and velocity at the centre of each cell, called the node, based on values of velocity and pressure of the surrounding nodes.

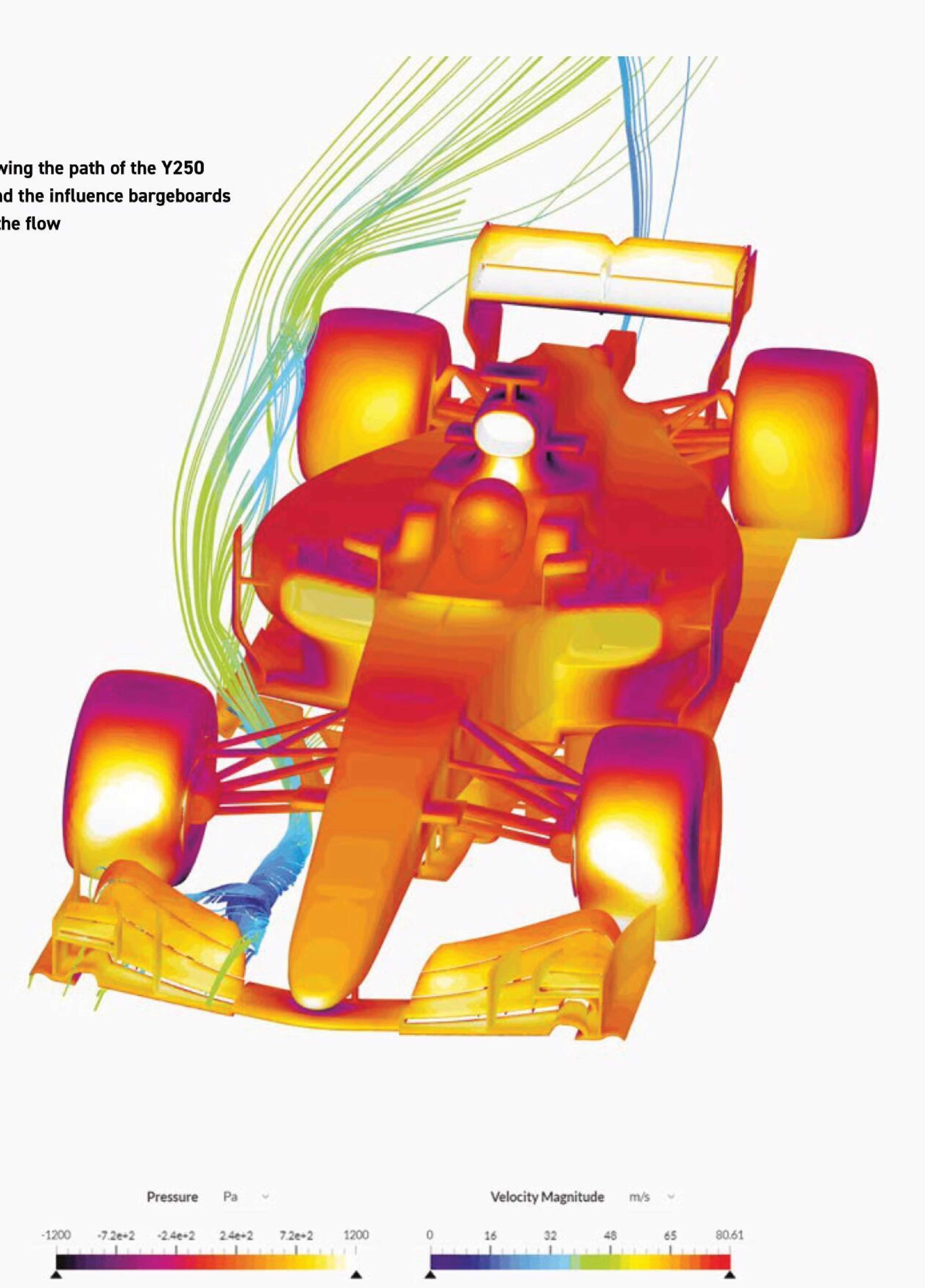
'The higher the order of these discrete approximations, the more surrounding nodes are included,' notes Remmerie. 'The reach of this technique is known as the computational molecule, resulting in a set of algebraic equations for each node. As the value of one node depends on the value of neighbouring nodes and *vice versa*, the equations are connected. To solve them simultaneously, they are collected together in a matrix.'

To solve a matrix, the discretisation error, which is the difference between the exact solution of the governing equations and the exact solution of the discrete approximation, must be understood. The more cells applied, the smaller this error. However, the more cells, the more equations need to be solved. High-density meshes typically contain millions of cells, and this quickly becomes very computationally expensive. As such, most CFD engineers apply high-density mesh to locations where the flow is complex, and lower density, larger cells where the flow is less so, typically further away from the object under investigation.

Once the mesh and matrix of equations are defined, it's time to solve them. 'It's possible to find the exact solution of this matrix problem through a direct method like Gauss elimination, or LU decomposition,' says Remmerie, 'but this is very costly in terms of computational power. This is where most engineers in motorsport use what is known as an iterative method.

'To explain that in short, this method starts by guessing an initial solution, which could even be a standstill flow field or zero velocity for every point. Then they linearise the equations around that point and improve the solution through iteration. If you iterate long enough, the flow field will converge to a stable solution, which reduces the difference between this solution and the direct solution of the equations, called the iteration error, and produces tangible results.'

Thanks to the ever-shrinking validation time for CFD, engineering teams are able to converge designs earlier in the development process, enabling them to bring results to the racetrack quicker, or more often, than was previously possible. Additionally, the methods inside CFD technology are changing, with new and different turbulence models providing more accurate representations of how a given design will work on track as the correlation with the wind tunnel is better than previous versions.



CFD showing the path of the Y250 vortex and the influence bargeboards have on the flow

SimScale

Workflow management

When it comes to the evolutions of design, quick start methods for CFD software have arrived where engineers can seed a simulation with the results of a previous one. The code for steady-state and transient flow methods have led to increased levels of fidelity never seen before, which are vital for those looking for that last one or two per cent, and many racing firms have access to such technology now.

Whether you're running a wind tunnel test or CFD simulation, it's vital to ensure the process is repeatable, and that there is a control element of the development. Without this, the number and effect of the changes made to a design are tough to identify and the development operations hard to analyse.

Enabling this control is one of the most significant areas of development in recent years, although it has not come from within the CFD itself. It is in workflow management, and its coincidence with the current generation of CFD-limiting regulations and resource management software installed on CFD processes. In all top-level motorsport engineering, workflow management is important, but it has become even more imperative in recent years as restrictions on development, and the time allowed for each, has been reduced year on year. Teams must keep control of CAD, simulations, prototypes, build of scale wind tunnel models and parts that get taken to the full-scale car, and all the design iterations of each in between, to ensure their finite resources are well spent.

Quantified recipe

'As a dev-ops company, you decide what your methods are, and then you quantify those,' says TotalSim US president, Ray Leto. 'Most F1 teams have a methods group that is always working to improve those methods, and define their CFD or wind tunnel testing recipe and then deploy those.

'Across the board in racing, teams have been using computer scripting, or checklists, or similar to make sure they've locked down the templates they use, and they don't modify those as a matter of course for the development to be measurable. This is a huge part of the development strategy in racing today.'

TotalSim has a tool called TS Results, which pulls all workflow elements together and provides a set of images, numerical data, video and charts to help analyse and characterise each development opportunity. Within it is a set of data analysis tools that allow the user to quickly go through and compare runs and move the design forward.

'Automating makes spotting trends, and the decision making after the experiments, easier as you're not having to create charts and understand what they are manually, it's all right there in a procedure,' says Leto. 'These workflows, and the automated post-processing and data analysis, enables a broader group of people to carry out CFD and understand it – a job that was formally only reserved for experts.

'Over the last five years, the development of workflow management tools has become a web-based interface where operators can tweak those templates and then deploy them into the operations group. That allows expertise and method verification to go out to all parties involved with the dev op and the teams get repeatable, tangible results.'

Resources allowed within any race series are continually changing, based on regulations and the technology available. Having the ability to cycle through development steps and get parts to the track on time is a base method where improvement can be made within a given period, and a given budget. Ultimately, that's the driver here.

Leto continues: 'Engineering in motorsport is not always about designing the ultimate part because that job is never done. It's a matter of pulling the trigger at the right point in the development cycle, getting parts to a track, and the decision for what the next targets are.

> **» 'Automating makes spotting trends, and the decision making after the experiments, easier as you're not having to create charts and understand what they are manually'**
>
> Ray Leto, US president at TotalSim

Draft & Conception

Design & Development

3D-Scan & Reengineering

BIGGEL ENGINEERING
idea concept design

info@biggel-engineering.de
www.biggel-engineering.de

+49 (0) 176 / 80 17 17 93
D-88079 Kressbronn

OUTPERFORM THE COMPETITION

WITH FASTER, MORE ACCURATE VEHICLE TESTING

TOTALSIM US

ACCELERATE EVERY STAGE OF DESIGN AND DEVELOPMENT WITH TOTALSIM US:

- Streamline pre-processing, post-processing, data management and more with automated CAE processes and workflows
- Perform highly-accurate CFD simulations with intuitive, web-based applications tailored to automotive designs
- Tap into our racing experience for on-track, wind tunnel and bench testing, performance mapping and aerodynamics analysis

EMPOWER YOUR TEAM WITH THE TOOLS TO OVERCOME CHALLENGES AND DELIVER HIGH-POWERED RESULTS.

CONTACT US AT 614.255.7426 OR INFO@TOTALSIM.COM TO LEARN MORE.

TOTALSIM.com

Aerodynamic Pressure Scanning rEVOLUTIONised

- Integral microprocessors
- Direct digital output

- Absolute & Differential measurement
- High accuracy 8, 16, 64 channels

Smallest and lightest pressure scanners available

EvoScann®

To request an EvoScann® demonstration or quotation call +44 (0)1264 316470 or email enquiries@evolutionmeasurement.com

www.EvoScann.com

'In motorsport, you don't have to make the best outright machine, it just has to be better than your competition, and that's the real finesse in understanding the resources and managing them in the best way possible.'

The efficiency of such a system impacts on all elements of the business, and the more it can be optimised, the less overall resource is wasted – a vital tool for the likes of Formula 1 as it moves into a cost-capped regime in 2021.

Cloud-based CFD

Traditionally, engineering companies required big, expensive hardware to run CFD simulations. But, since the advent of cloud computing, an endless amount of power can be accessed from a web browser provided you have access to the internet. Engineers can now access CFD platforms from a tablet, or even mobile 'phones, so teams that are not in the same building can collaborate and log in to the same project. Though the ease of use is impressive, the most considerable advantage of cloud-based simulation is its speed and scalability.

'What is available now is GPU-accelerated simulation through cloud computing, which is where you're taking the speed of simulation and improving it by an order of magnitude,' says Dr Naghman Khan, business development manager at SimScale. 'A contract stimulation that takes two days to solve on traditional hardware now takes just four hours. Speed is the primary driver for the cloud computing CFD space.

'Additionally, as the software are always improving in the background, often when you log on there are new features, better accuracy and higher performance. Whereas traditionally a software vendor might have one software release per year, with cloud-based simulation it's in real time, so you get those features instantly.'

CFD study of a contemporary Formula 1 car front wing displaying the flow over and through the elements

» **'A contract stimulation that takes two days to solve on traditional hardware now takes just four hours. Speed is the primary driver for the cloud computing CFD space'**

Dr Naghman Khan, business development manager at SimScale

CFD showing the air stream underneath a formula car, and exiting at the diffuser

SimScale

SimScale

To continually check and improve the accuracy of the CFD code, cloud-based computer-aided engineering software firms complete validations daily.

'We validate every element of the software every night to make sure nothing has changed,' explains John Wilde, vice president of product and customer experience at SimScale, 'and we do this very thoroughly before we release anything new in the solvers. These are very comprehensive – there are 400 or so of them – and now and again we do the industry standard validations, which everyone that has a CFD code or FEA code has to adhere to.

'We also run simulations on a test suite, then validate the test suite to ensure we are right every single time.

'The validations are translating the physics to the numerical solvency scheme with the output question, "are you getting results that are within a certain tolerance of the measured experimental and empirical results?" There are now AI tools that speed up this process of solving the partial differential equations by a factor of 10, which helps validate far more information in a much smaller space of time.'

SimScale uses machine learning, but not to predict results, instead to measure average mesh counts, core hours and cost. 'We choose the right machine for a project to be used on, and that is cost efficiency, which is what we optimise for,' says Wilde.

For racecar engineering, SimScale has an LBM solver called Pacefish, which is the most widely used solver when it comes to investigating downforce and drag. 'It's so fast that we at the moment don't need to optimise it to make it faster,' says Wilde. 'The next step for this technology is to figure out roughly what the flow is going to look like and then iterate from there.'

Parallel processing

Another massive advantage of cloud computing is parallel processing, as Dr Khan explains: 'Parallel processes are useful from early-stage design right through to detailed engineering simulation. With cloud-based CFD, at the early-stage design you can rapidly get through multiple different design scenarios and start converging quickly on an optimal final solution, and then use a more detailed engineering simulation for the finer measures to get more accurate results.

'The huge scope here gives teams the capability to do that quickly and iterate through the first designs far quicker than a traditional CFD outfit running hardware in house.

'For example, for surface aero investigations, teams can run any number of cars, each with different aero packs, all at the same time in parallel. Doing it this way, you can run multiple design iterations and get the results at the same time, and look at them at the same time and compare them all at the same time. You can also change the angle of incidence to the car in the parallel tests to get an understanding of how it performs dynamically.'

Cloud computing's immense power means teams can now build their entire working environments in a virtual wind tunnel. Functions include modelling air temperature, pressure, moisture levels and much more. For endurance, or 24-hour races, it's possible to assess night and day running, and even the transition between the two – a vital aerodynamic study for those trying to optimise cars for such races.

Future development

Coming to the forefront at the moment are sophisticated, reduced-order modelling software packages where AI tools are used to provide solutions, should there be enough data available to train the AI tool. AI training tools include response surface modelling, surrogate modelling and reduced-order modelling techniques where sub-models are used to teach the computer the behaviour of some elements of the design and then use them as a substitute for the higher-order models.

AI tools are very good at interrogating complex flow structures by looking at sums of forces and average off-body flows and then isolating them from the data about the entire flow field where much of the additional information is not required. These tools are also able to accurately re-write states after a given use phase so engineers can digitally study the wear effect on parts, such as fluid film bearings for example.

Engineers can then use data from these studies to feed the next stages of development to reduce the weight of a part, its form factor, cost and / or change the material it is made from for better performance or efficiency.

When AI and machine learning tools are applied at a system engineering level, it is easier for teams to visualise and understand the trade offs on all design and development inputs, whether it's the CFD or wind tunnel or FEA studies, and understand the sensitivities of each.

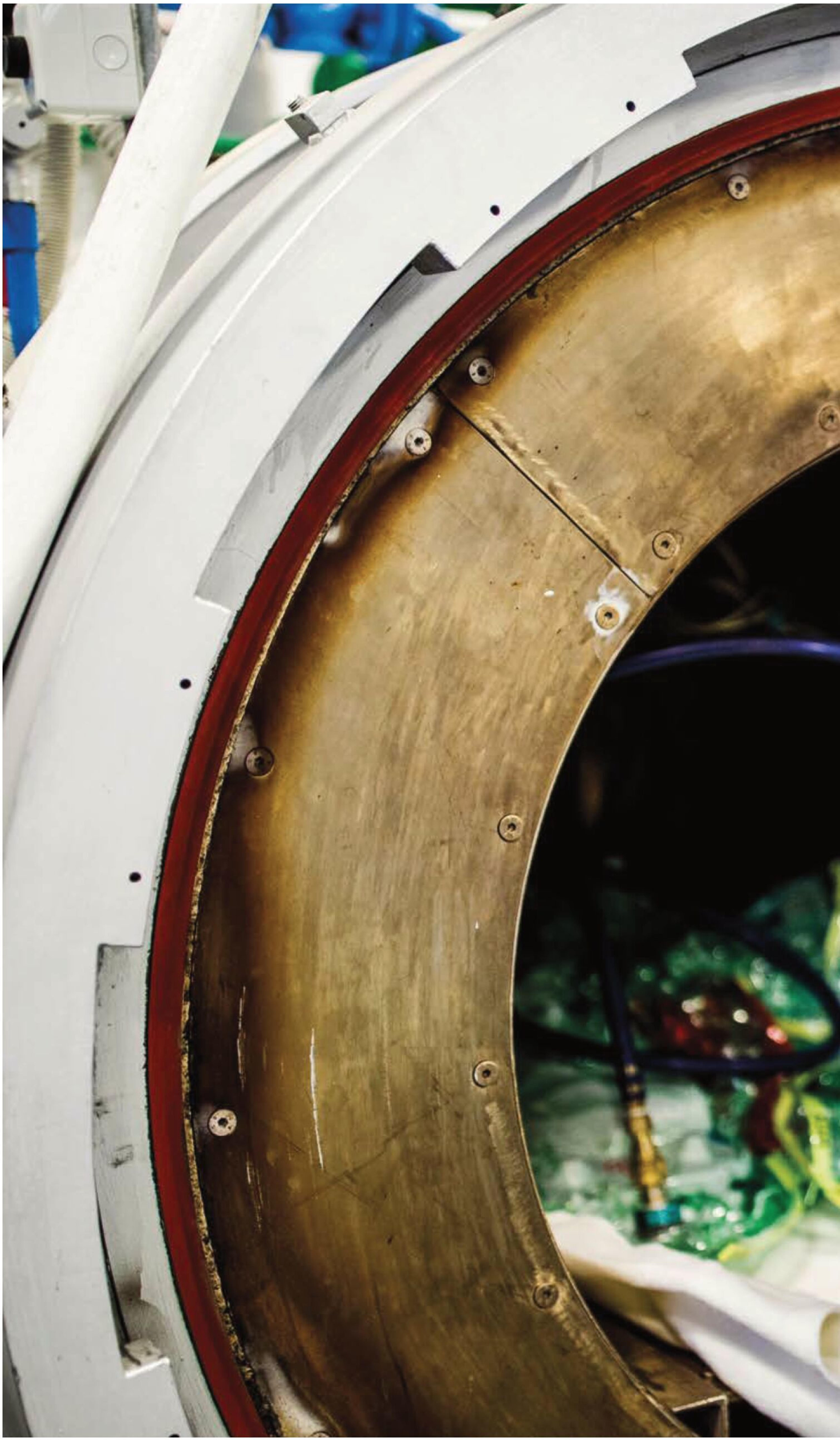
The next evolution in this technology is the ability of the systems to help engineers allocate appropriate resource to tasks as a function of the influence of all inputs, so teams spend their resources in the right areas to find the performance they're looking for.

» The next evolution is the ability of the systems to help engineers allocate appropriate resource to tasks as a function of the influence of all inputs

Hot tubs

Carbon fibre monocoques lie at the heart of most top-level racecars, and they're a complex piece of engineering in their own right. *Racecar* investigates

By Lawrence Butcher



Under the skin of any modern racecar, at least of the Sports Prototype or formula variety, is the tub, or monocoque. A multi-functional component that must fulfil many design requirements, some of which are diametrically opposed.

Its primary role is to fill the void between the front suspension and the engine, providing sufficient structural stiffness for said suspension to operate correctly. At the same time, it must safely house the driver (to varying degrees of comfort, depending on the application), the fuel cell and, as is increasingly the case, an energy storage system (ESS) for either an electric or hybrid drivetrain.

Additionally, the tub must be as light as possible, while also having as minimal effect on the overall footprint of the car as is feasible. Aero is a predominant concern and, as such, the monocoque, just as with the powertrain, cooling system and any other ancillary components, plays second fiddle to aerodynamicists' desires when it comes to real estate.

Think of the shape of a modern Formula 1 tub. It is not through choice that the driver sits with their legs up in the air, with the chassis cut away sharply below. The form is driven by the need to channel as much air as possible under the nose of the car.

Composite parts being readied for curing in one of AlphaTauri's autoclaves

» A racecar's monocoque is one of its single most complex components, a blending of advanced engineering and artisan skills

A sizeable autoclave is required for curing monocoque structures

The similarity to a wool loom is not coincidental, composite strands are woven together on just such a device

All of these competing demands need to be balanced out. Ultimately there will be compromises, but with contemporary design, simulation, manufacturing methods and materials, they can be reduced.

Of course, racecars have not always been built this way. The spaceframe chassis ruled supreme until the early 1970s when aluminium monocoques started to become commonplace, and remained in use, including in Formula 1 and Sportscars, until the late 1980s, when carbon fibre took over. Though designers had dabbled with the material in the 1970s, cars such as John Barnard's McLaren MP4/1 revolutionised racecar chassis construction, first in Formula 1 and then other series. Relying on a combination of uni-directional carbon fibres and aluminium honeycomb, those cars laid the groundwork for much of what still exists today.

Design implications

As noted, the design of a car's tub will be a delicate balance of trade-offs. The smallest detail needs to be considered, especially at the highest levels of racing where tiny percentages can be a significant performance differentiator. Take the example of the then Force India team in 2015. Driver, Nico Hulkenberg, was 8kg heavier than team mate Sergio Perez. To account for this, the team built him a lightweight chassis to maintain leeway for ballasting the car. The compromise with the lighter chassis was it was less stiff, which was detrimental to suspension performance, but not to the extent that it offset the gain from the greater freedom to place ballast.

This is just one example, there are many others such as the relatively regular occurrence of a team needing to switch engine or power unit supplier late in a car's development cycle. Invariably, this leads to compromises as tubs are inherently long lead time parts, so it is impossible to tweak the design to perfectly match a new engine's specifics.

Architecture

At a basic level, there are a few common features of monocoques across car types. The rear bulkhead will have mountings for the engine, the exact layout determined by whether this is a stressed or semi-stressed part. These will be in the form of inserts bonded into the carbon, which have to withstand both the forces generated by the powertrain, and those of the suspension and aero.

The rear of the tub will feature a rollover structure that must tie into the rest of the monocoque securely enough to resist extreme crash forces. Most rule sets also require the tub accommodate a car's fuel cell, which is positioned as centrally as possible. This is not simply a safety consideration, it also helps to maintain balance regardless of fuel load.

Moving to the centre of the chassis, regulations usually dictate the minimum volume for the driver's cockpit, as well as elements such as compulsory side impact structures. From these fixed points, the rest of the tub's geometry can be calculated.

The front of the chassis can be something of a packaging nightmare. Frontal area will be kept to an absolute minimum for aero purposes, while the driver's feet, pedals and various suspension elements are all competing for space. At the very least, there will be two dampers and a third element, with either coil springs or torsion bars, the latter also requiring mountings incorporated into the tub.

Then there are components such as the steering box and mounting points for the wishbones. Again, aero rather than packaging concerns tend to dictate their location, often leaving structural engineers with a headache. Finally, there will be the mountings for the nose, which incorporates the front crash structure. These have to be substantial enough to both survive an impact, as well as carry the aero loads from the front wing.

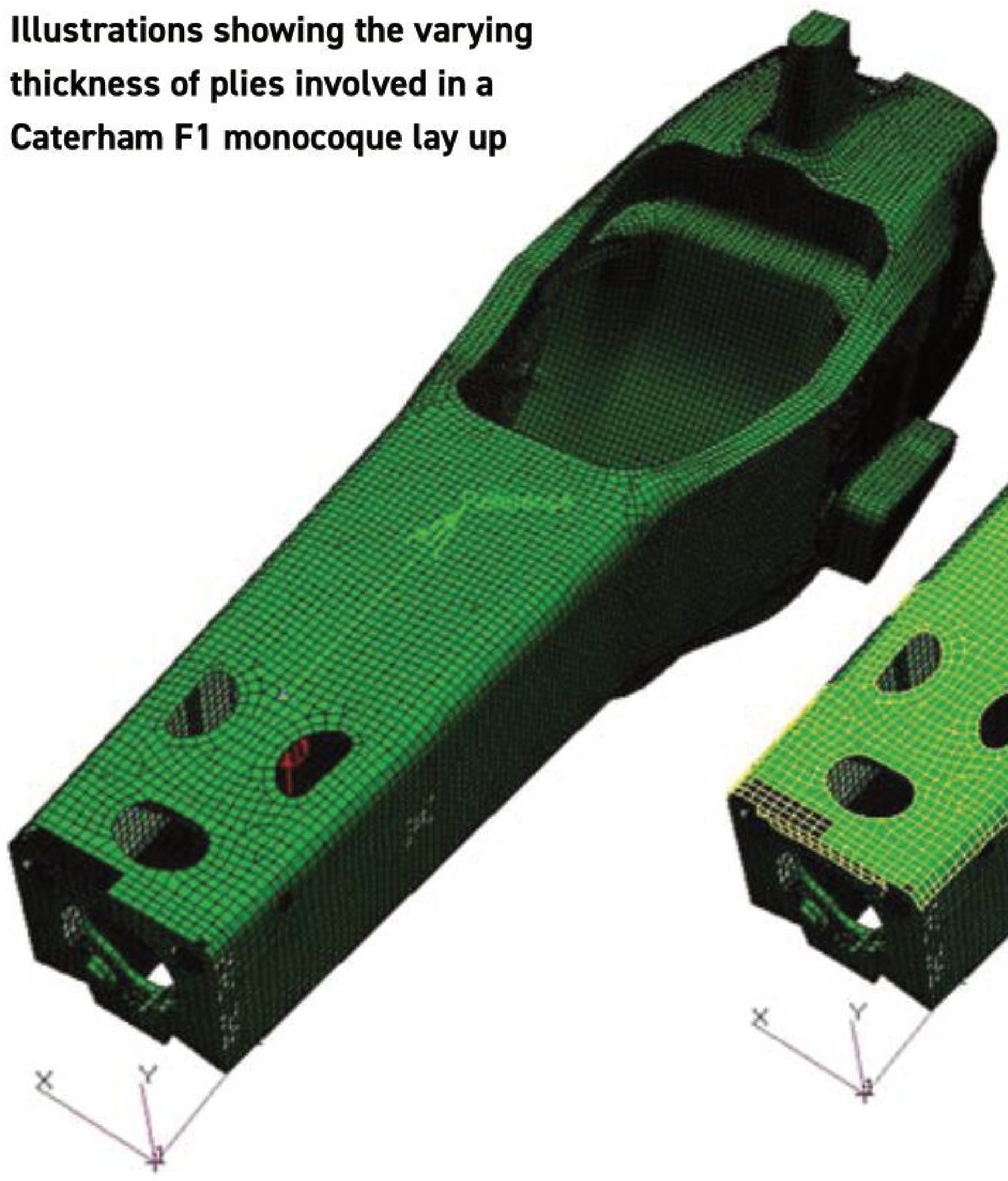
Composite parts are placed into a vacuum bag prior to curing

There are a myriad other details that need to be considered in the design and construction of a monocoque, such as the cost implications of various design choices which are not considered here, but this overview gives some idea of the complexity involved.

Materials and processes

A modern F1 car is approximately 80 per cent carbon fibre by volume (yet composites only account for around 25 per cent of the mass). The lay up of the material is a complex and time consuming process and, though automation is increasingly used for the production of composite parts in general automotive, racing tubs are still very much handmade.

Even the simplest carbon fibre part consists of a combination of elements, the relationships between which will have a significant effect on the part's strength, Illustrations showing the varying thickness of plies involved in a Caterham F1 monocoque lay up



Laminate optimisation of a Caterham F1 chassis showing the various laminates used, including cored materials

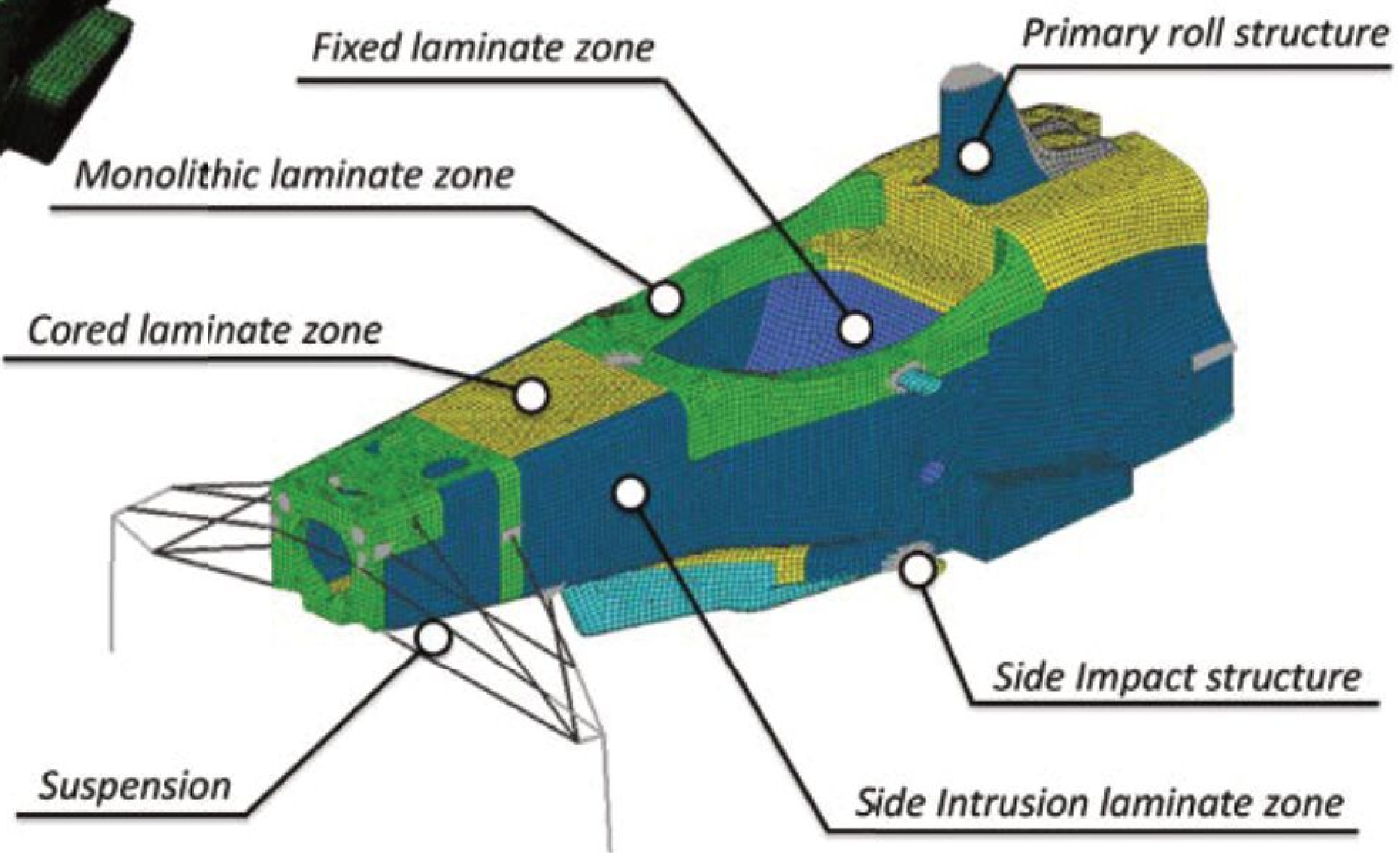
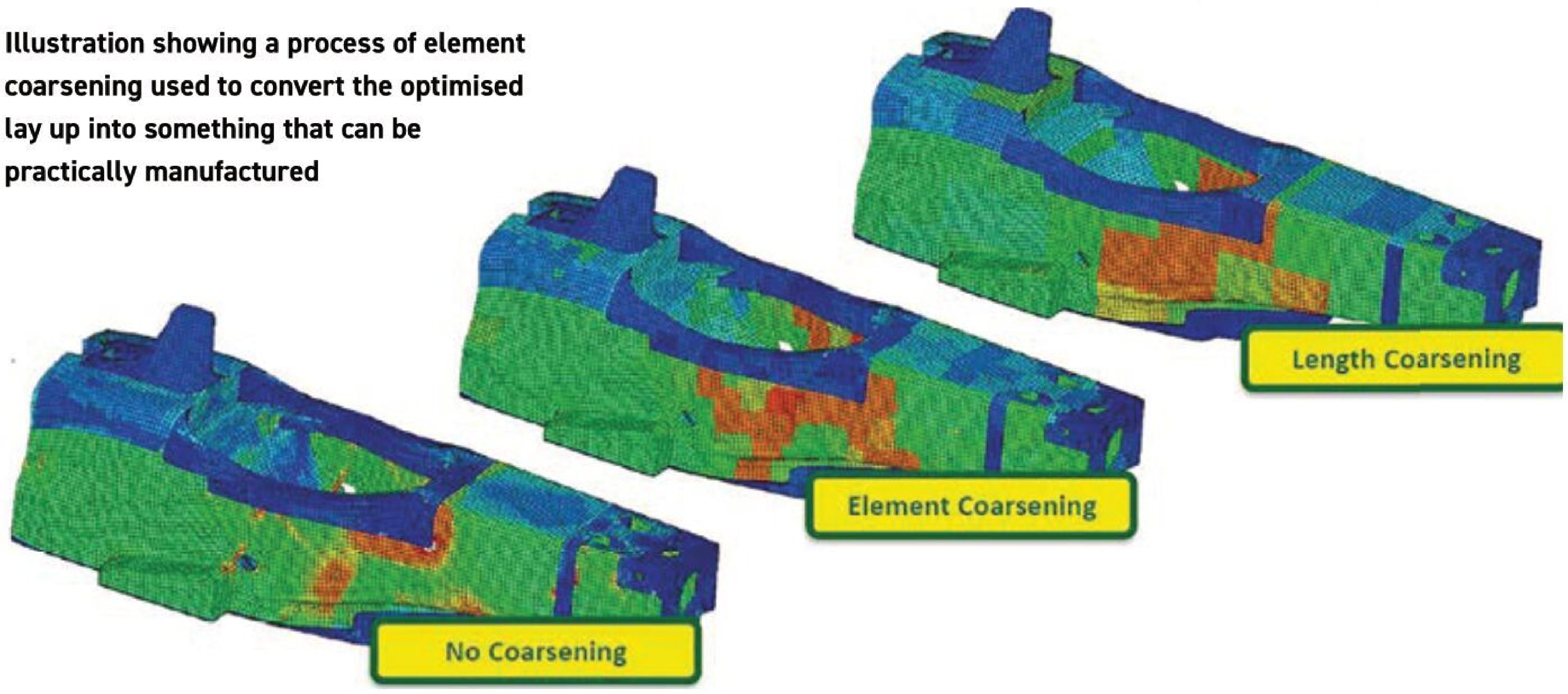


Illustration showing a process of element coarsening used to convert the optimised lay up into something that can be practically manufactured



» Resin is the weak link in the material, so the higher the proportion of fibres to resin the stronger a part will be for a given volume

stiffness and weight. The raw carbon fibres are produced by the controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursors that are already in fibre form. The most common precursor is polyacrylonitrile (PAN), although fibres can also be made from pitch or cellulose. Varying the graphitisation process produces either high-strength fibres (processed at about 2600degC) or high-modulus fibres (processed at about 3000degC) with other types in between.

Once formed, a surface treatment is applied to the fibres to improve matrix bonding, and chemical sizing to protect it during handling. Fibres are commonly grouped according to the modulus band in which their properties fall. These bands are commonly referred to as high strength (HS), intermediate modulus (IM), high modulus (HM) and ultra-high modulus (UHM). The filament diameter of most types is about 5-7µm.

At the most basic level, individual carbon fibres are bonded together by a resin system. Normally, the fibres will be spun together to form yarns, which can then be woven into a variety of fabrics and tapes. These can be uni-directional weaves, where the fibres are all aligned, plain weaves (with yarns aligned at 90 degrees to each other in an under / over arrangement), twill weaves, spread tows etc. A chassis will be formed from a range of fabrics (mostly pre-preg, thermosetting materials that are cured in an autoclave), arranged in a number of layers, known as plies, to make up a single thickness.

Under pressure

In the past, 'wet' lay-up methods were sometimes used, which are very similar to those employed in GRP construction. Today, pre-preg materials are almost universally used. These are sheets of carbon fibres pre-impregnated with resin which, when cured under pressure and heat, give excellent strength characteristics with a low resin / fibre ratio. This is beneficial as the resin is the weak link in the material, so the higher the proportion of fibres to resin the stronger a part will be for a given volume.

The various fabric sections are laser cut and then laid into either an open or closed mould, according to a strict set of lay-up instructions, known as a ply book. This dictates which plies go where and in what order. The moulds will also normally be made from carbon, formed over a pattern, to provide the necessary stiffness during autoclaving.

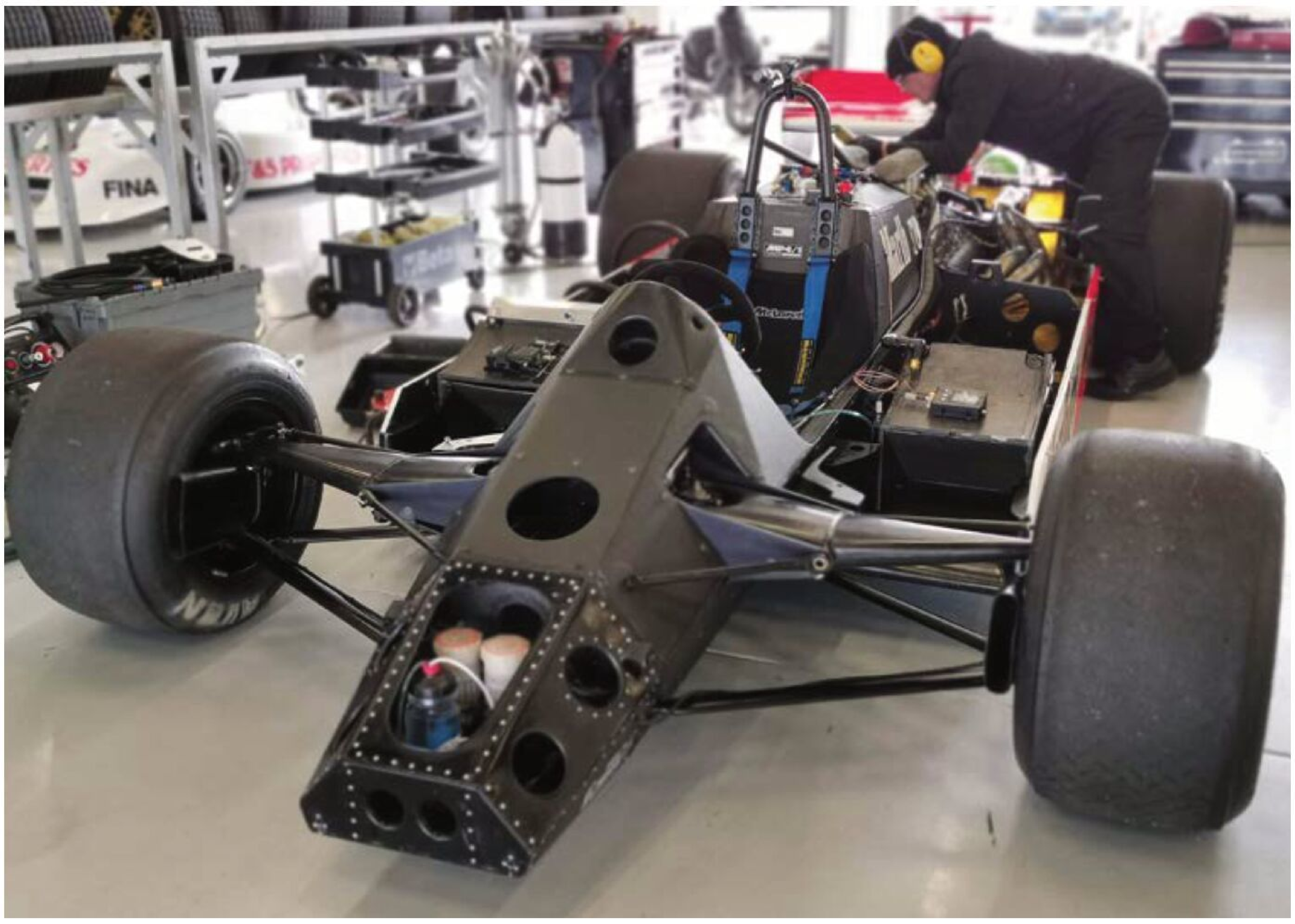
Pattern making

The patterns are produced from a material known as tooling board, or PU foam, which has good structural strength while still being easily worked. Generally, tooling board is used when pre-preg material is involved, as it maintains its shape and structure better when subject to the high temperature and pressure in an autoclave.

Patterns for large tub parts are machined using five-axis CNC routers with very large beds. For smaller parts, there is an increasing trend towards the use of additive manufactured patterns and moulds, but not for entire chassis sections. The monocoque will be made in two or more sections initially, and then for final assembly plies will be wrapped around the entire structure making a single, homogenous part.

Some of the latest materials to arrive on the market are 'spread tow' fabrics, where thin tapes of individual fibres, rather than spun yarns, are woven together. The low crimp (where the fibres intersect) of spread tow fabric gives a similar mechanical performance to cross-plied, uni-directional (UD) fibres, while also incorporating the benefits of a fabric, such as drape and a decreased risk of delaminating.

» Material layout within a part is optimised for a given set of loads, boundary conditions and constraints in order to maximise performance



For impact protection, aluminium and Kevlar honeycomb structures are built into the tub, and increasingly Zylon panels, too

By using a spread tow fabric, the weight of the woven reinforcement can be reduced while maintaining, or improving, mechanical performance. Rather than using two or more plies of UD, a single ply of spread tow can suffice. The low crimp factor also leads to reduced void content (the appearance of pin holes in the surface), compared to traditional fabrics, reducing the quantity of filler material needed to create a smooth surface finish.

Core strength

Honeycomb structures of aluminium, Kevlar or Nomex are often used sandwiched between plies of carbon, and are a key ingredient in creating stiff, light components. This construction achieves a stiffer structure for a given weight than if only carbon plies are used. Honeycomb materials will vary in thickness from 5-12mm and, in areas that are subject to intrusion or crash tests, higher density types can be used to provide the necessary impact protection.

The honeycomb sections are incorporated during the lay up process and are bonded to the inner and outer carbon skins using high strength adhesive sheeting. PU foam is used in much the same way and, thanks to its ease of shaping, is ideal for forming complex wing geometries. Again, shaping is undertaken on CNC routers.

Often, materials other than straight carbon fibre will also be incorporated into a tub. For example, Zylon is used extensively to provide intrusion protection in many top-level machines. In fact, the LMP3 chassis rules were recently updated to include the use of panels made from the material on the cockpit sides.

Inserts and joints

There are many areas where it is necessary to incorporate metallic components in a chassis composite structure, including the aforementioned suspension and engine mounts. These inserts normally take the form of threaded 'top hat' sections. In the early days of composite construction, creating reliable bonds between carbon and metal sometimes proved problematic, but current working practices have developed to an extent where this is no longer a problem.

Titanium is the favoured material for inserts, thanks to its light weight, high strength and a coefficient of thermal expansion similar to carbon fibre. It is this third factor that is most important to structural integrity, as the possibility of cracks in the bonding material are less likely to occur after repeated thermal cycles. For this reason, aluminium, which has a different coefficient of expansion, is rarely used.

Prior to bonding, close attention will be paid to the surface cleanliness of the metal part, which will be subject to both media-based and intensive chemical cleaning processes. Any contamination can lead to a premature failure of the joint.

Simulation

So how does a manufacturer decide on which materials to use, where they are placed and what shape they are cut to? It is here that topology optimisation (TO) comes into play, whereby material layout within a part is optimised for a given set of loads, boundary conditions and constraints in order to maximise performance.

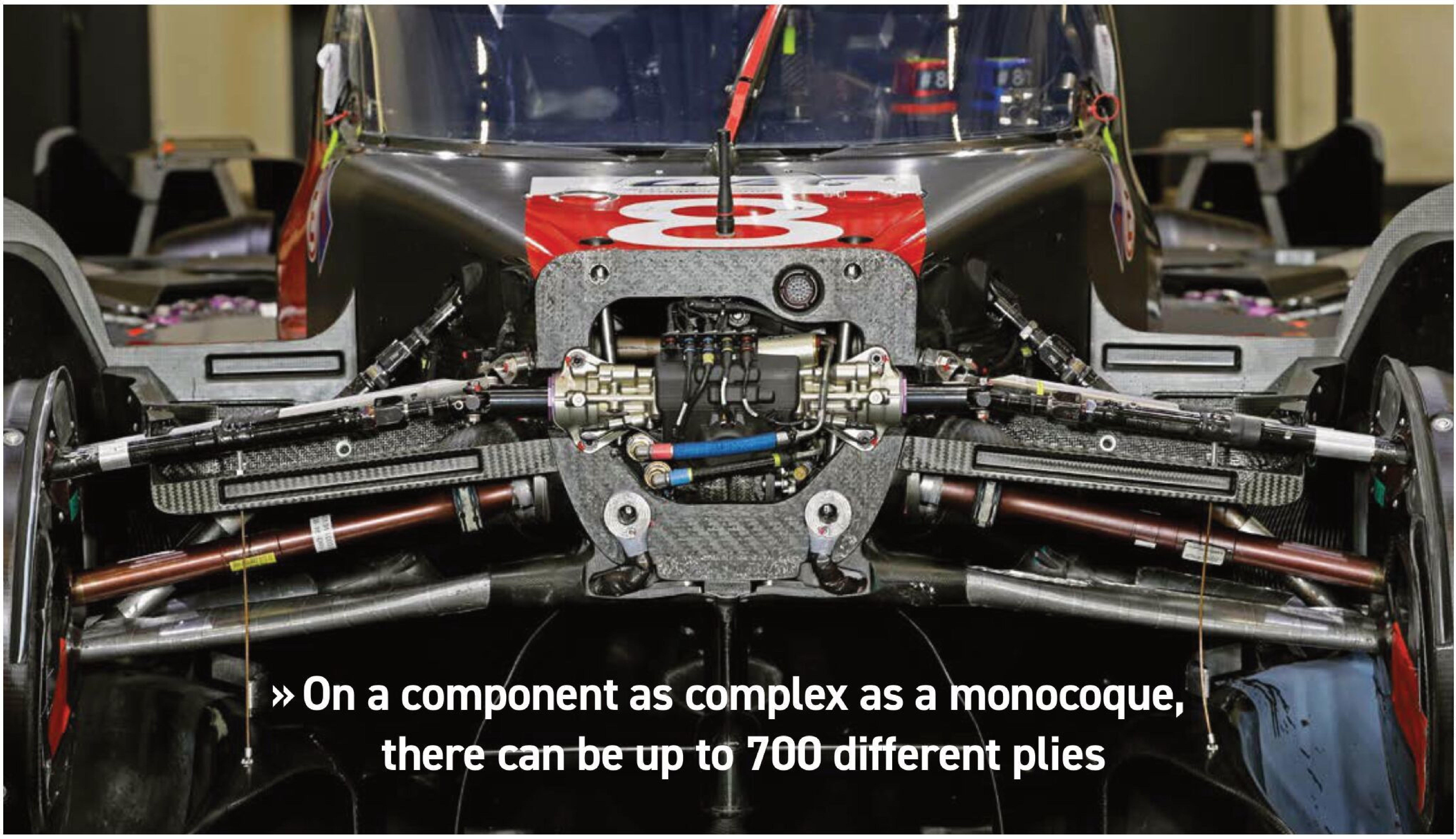
In the case of carbon fibre parts, this process is technically known as topometry optimisation, as it concerns the sizing and arrangement of composite plies, rather than the final form of the finished product. In terms of a tub, the ideal end result of the application of TO is to minimise the number and thickness of plies used while still meeting the various stiffness and strength characteristics.

It should be noted that automated topology optimisation has been around for some time, but it is not a silver bullet for all of an engineer's optimisation needs. Parts still need to be manufacturable and, as with any mathematical analysis system, the input data on material properties needs to be accurate.

When dealing with metals, this latter point is not a big concern as there are extensive databases of almost any grade of metal. A metal part will be made from a single, homogenous lump of material, something a carbon composite part (the name gives it away) is definitely not. The process of accurately simulating the behaviour of a carbon fibre part is a complex affair.

First, the materials used for each ply, as well as the resin system, must be characterised, which provides the basic inputs to any analysis. If this is not done correctly, the results will be unreliable. The characterisation process involves testing many different 'coupons' of material. These are flat pieces of cured carbon fibre, which are subjected to various tests to ascertain the material's structural properties.

This provides the basic inputs for analysis, but for complex laminates that comprise different plies and mix different weaves and tapes, running at the limits of their design capabilities, further analysis is needed. This involves delving deeper into the properties of a material than simple characterisation tests can provide. For example, the microstructure, how the fibres are orientated, how many fibres there are, the shape of the fibre and the type of matrix all need to be considered, as well as the curing process and parameters that control it.



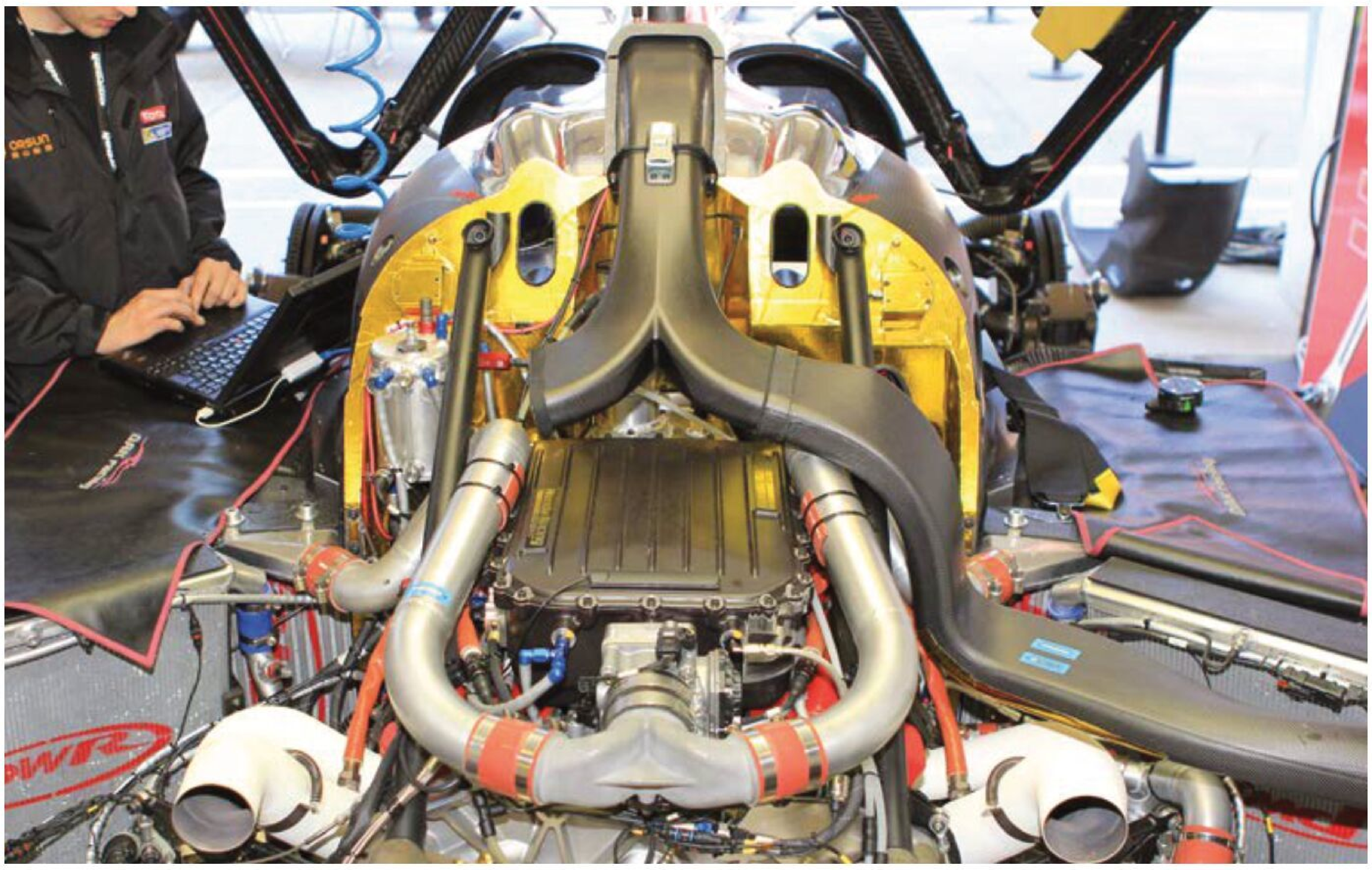
» On a component as complex as a monocoque, there can be up to 700 different plies

Pic: Lawrence Butcher

This image of the front of Audi's R18 LMP1 shows just how tightly various components are packaged at the front of a tub, and also the fixings for the nosecone structure

Once materials are decided upon and reliably characterised, the lay up of a part can then be optimised – be it a tub, wishbone or wing – to ascertain the ideal combination of plies, their orientation and type. That can be achieved using traditional CAD software and FEA analysis and some well-resourced teams will have their own proprietary software to achieve this.

However, there are also dedicated programmes available to arrive at a near-perfect composite structure, some of which come as part of more general simulation packages. These systems need to account not just for the types and placement of various plies, but also the impact of fabric being draped. For example, one might start with a 45-degree fibre but, by the time it is curved around complex shapes, it is nowhere near that.



Pic: Lawrence Butcher

The engine installation in a Ligier JS P2 shows how the PU mountings are integrated into the rear bulkhead of the tub

Software advances

The historic route for developing a composite component would be for someone to design a surface model of a part, and then a structures engineer would assess it and suggest a combination of uni-directional plies and cloth, and an FEA model would be built up using those assumptions. With the latest advances in software, instead of having to try multiple different iterations, an engineer simply provides the materials available, together with the loadings, and the software works out the ideal layout of plies. On a component as complex as a monocoque, there can be up to 700 different plies.

Dedicated software tools are then needed to create cutting models for the various parts and create the ply book, for use by the fabricators when laying up the parts. Surprisingly, despite the power of the simulation software, these still tend to be produced using Microsoft PowerPoint!

It is then down to the skills of individual laminators to ensure the final product is an accurate representation of the original design. Each ply must be placed in exactly the right orientation, and the curing process followed precisely to achieve the correct structural performance throughout.

Though the finished product is a one-piece carbon structure, a racecar's monocoque is one of its single most complex components, a blending of advanced engineering and artisan skills.

Only once the finished tub emerges from the autoclave, is cleaned up and, for certain unfortunate specimens, subjected to crash testing, will the engineers know if the potentially thousands of hours of effort put into its construction have paid off. Their hard work is then covered up by bodywork, only coming to the fore in the event of it saving a driver's life during a heavy shunt.

Take Control of your Systems!
Your Partner for Intelligent Flow Control

New

COOLING PUMP FOR POWERTRAINS

Extremely small with high power density

NEW

- Lightweight: 350 g
- Powerful: 50 l/min @ 1 bar
  (up to 80 l/min)
- Integrated control electronics
- No metallic abrasion
- CAN, UART, LIN, etc. available

Centrifugal Pump IFC 3000-1

About

We develop intelligent systems that control the flow of various media in the vehicle for top motorsport applications and small batch series:

- Battery temperature control
- Inverter temperature control
- Electric motor cooling
- Brake-by-wire
- Gearbox cooling
- Combustion engine cooling

\- Sensored or Self-sensing BLDC Motors - Electrically Controlled Pumps - Preheaters - Valves

\- Pit Equipment - Impellers - Mixing Valves - Connection Systems - Pneumatic Systems -

www.sobek-motorsporttechnik.de

SOBEK

The comfort zone

In the quest for performance, driver comfort can take a back seat, but there's a great deal of engineering in cockpit ergonomics

By RICARDO DIVILA

Motor racing design for the engineer means work in aerodynamics, mechanics, physics and chemistry. Often, one of the items that usually goes by without much comment is entirely dependent on biomechanics and biology – the driver. But the person behind the wheel is not entirely forgotten when it comes to designing a racecar, for we also have ergonomics, or the study of human-machine interfacing, to think about.

Ergonomics is actually a multi-disciplinary field in its own right, in that it encompasses and amalgamates physiology, anatomy and medicine on one side, as well as psychology, physics and engineering, plus anthropometry.

But for too long racecar design seemed to follow the Procrustean school rather than the ergonomic school. According to Greek legend, Procrustes was an inn keeper who either stretched his customers if the bed was too big for them, or chopped off bits of their legs to make them fit. If you have ever driven a vintage racecar, this will not be news to you.

But the vehicle cockpit should serve the driver, not the other way around. The more driver-friendly the ergonomics are, the more comfortable the driver will be, and the better they can focus on driving. Considering the driver is already working in a difficult environment – a hot, noisy and vibrating one – as well as being subjected to *g* forces the body was not designed to cope with, anything that interferes with their performance will mean slower lap times.

Even in the best designed racecars, with an ideal layout, power and aero, having a bad fit can cost consistent lap time. A better driver fit sometimes gives a one-second gain, hard to achieve with other means and considerably cheaper. It just demands some time.

There are two pitfalls for designers, one is designing the car around themselves, so it can feel okay to them but be unusable for a different sized driver. But there are standards for all movements and forces used by the driver to control the car, derived from operating machinery, which will cover most sizes of driver that could conceivably operate it and be used for design. The other pitfall is forgetting the problems brought in by the forces a driver is subjected to under high *g* loads.

Tailor made

If you are designing for a particular driver, you can dimension a cockpit to them, but there are still several parameters you must observe, governed by their particular dimensions, to ensure best performance. If designing a Formula Student or solar-powered car, the usual university projects, then find the smallest, lightest member of your team and conscript her or him as a driver so as to make a smaller vehicle. Even companies making LMPs can use this approach, but a word of warning here: I have been involved in a couple of projects that fell foul of driver changes, when the newcomer was taller than the driver the car was designed for.

The most important part of a car for operating it is its seating position. It will affect the driver's field of view, both forwards and vertically. The field of view should include visibility ahead and to the sides of the vehicle and visibility of the road surface. Forward and lateral should cover at least a 180-degree arc. If the drivers must twist their neck to see enough to feel confident, their field of view is inadequate and the seating position should be improved. Remember, view is already limited by the dimensions of the helmet opening.

» **If the drivers must twist their neck to see enough to feel confident, their field of vision is inadequate**

When designing a car's seat position, the ideal place enables the driver to see clearly ahead and beside themselves through standard and peripheral vision, and to adequately see the side mirrors in the latter, thus not needing to continuously take their eyes off the road ahead to gauge an opponent's position behind them.

Open cars have an advantage here, while enclosed cockpits can bring additional problems. For example, the push for competitiveness can take driving positions to extremes, to such a point that the combination of regulations for LMP cars drove both the design and layout, pushing the driver forwards.

Having small rear wings and a limited rear diffuser size and angle led to the LMP teams shifting the c of g forward by moving the engine forwards, resulting in nearly equal weight


Due to multiple drivers, LMP cockpits need to be designed to accommodate a range of body sizes


The spaceframe of Divila's Formula Vee project. The ergonomics of a design must be considered at quite an early stage

distribution front and rear, and allowing more aggressive front splitters to generate more downforce at the front and claw back total CL. The resulting increase of front tyre sizes (width and diameter) to cope with the added loads ended up in LMPs having a limited view forwards, nearly akin to looking through a letter-box slot due to the increased size of the front wings. It became so critical that the FIA / ACO ended up issuing regulations to fix the driver eye position by giving visibility templates and seat position templates to avoid the problem.

These FIA dimensions can be a good guide for the design of any racecar, as they are based on the experience of the organisation and its goal of making racing as safe as possible.

The use of mock-ups is a hallowed tradition, from simple plywood boxes that can be tried out by the driver to fitting him or her to the base spaceframe, monocoque or bodyshell to define the control positions.

» If you have a GT or a Touring Car with a rollcage, it is recommended to pad all tubes within striking distance of head and limbs

Always remember to think about the lateral and longitudinal *g* forces that will be acting on the driver at the track. The seat should be firmly fixed and capable of handling the *g* loads in the case of a crash, too. And keep in mind the driver's 'feel' of the car is through the seat of the pants and the torso, when they are correctly supported in the seat.

Regulations usually give head clearances from the roof or a line across the roll-over structures, so make sure the driver is in the correct place. I have seen too many drivers scrunch down to fit in a cramped closed car and even single seaters. It is a stupid thing to do and the engineer should make this clear to the driver, as seatbelt straps stretch under the loads that can be encountered, so does the body. It is in the driver's own interest to conform.

If you have a GT or Touring Car with a rollcage, it is recommended to pad all tubes within striking distance of head and limbs to protect on impact.

Control freaks

Having defined seating position and visibility, the next items to investigate are the controls and instruments, starting with the steering wheel. For best car-positioning control, the steering wheel should be placed at a height that clears the thighs when moving and does not interfere with forward vision. The angle to vertical should not give too much extension of the arm with lock. Having the arm fully extended should leave the wrist sitting on top of the wheel. The ideal position should ensure the driver uses the biceps to turn, not the forearm, as these are stronger. But single seaters with power assistance can just use forearm force.

The geometry of the suspension actually makes the driver lift the car when putting lock on as it pivots around the king pin and caster axes, so forces can be quite high, especially when you add aero forces. Before we had PAS (power assisted steering), as downforce went up caster was gradually reduced to help reduce steering forces, and when ground effects came in we ended up running zero caster and zero king pin angle and using trail axles – the axle centreline was behind the line between top and bottom balljoints to give the caster effect.

One of my drivers, a world champion, stated that the limit in the corner was probably higher, but he was not confident enough that he had the strength to catch it if the car stepped out, due to the steering effort needed. Indeed, Nigel Mansell was probably as successful as he was because of his sheer physical strength.

But too high a steering effort makes it fatiguing and also difficult to feel the limit of the car. There was a period when steering wheels became very small, tucked under the cockpit rim to allow a small cockpit opening and increased chassis torsional stiffness.

My own views on steering wheel sizes come from a discussion with Ayrton Senna about driving techniques and design parameters. He maintained that delicacy of driving depended on lightness of effort, allowing him to feel the self-aligning torque. So not too light and dead feeling, but with a steering wheel size that would give more movement for the same angle.

If you have driven a kart, which has a very direct steering ratio, close to 1:1, you will know that if you come out of a kart session and immediately drive a road car you experience a sense that the car has very slow steering, as your short term muscle memory has been re-set to the direct ratio, so the road car yaw rate response will feel very slow.

Senna felt strongly about this and eventually prevailed over the design team to get it to fit a bigger diameter steering wheel on his car when time came for a new design, despite objections from the engineers about the difficulty of maintaining structural stiffness. This particular racecar reversed the paradigm of small wheels, where the design was decidedly Procrustean.

Subjective preferences

The above shows that drivers can learn to drive very difficult cars with bad ergonomics just by getting used to their habits, but they could be improved by using proper parameters.

But I must emphasise here that all this has a subjective element. Different drivers will have different requests, either because they are used to something as they have previous experience from other cars, or because of the way they developed their driving style.

The yaw rate response needed for different racecars depends on track conditions. A Formula 1 car generally uses a ratio of between 8:1 and 11:1, IndyCars on ovals use a ratio of 20:1, with a larger diameter steering wheel for more precise steering on high-speed banked ovals. That reduces clearance for hands in the cockpit, but this isn't a problem as the drivers don't need it.

The muscular effort needed to steer a traditional Formula 3 car, which has no power steering, is surprising

You need to give the driver enough space to turn the steering wheel

» Controls that are awkward to reach or difficult to operate will distract the driver, and can result in driving mistakes

For road and street circuits, IndyCars go back to a smaller diameter for a quicker response.

GT cars and modified production cars sometimes have to use the original suspension points as homologated, so you can make a car more responsive by having a smaller diameter steering wheel, within reason, and PAS can iron out any extra effort needed by the driver. Alternate pinions on rack can also be changed.

To give an idea of the forces involved, consider the muscular effort in a lower single-seater formula without PAS, like a F3 or F4. When measuring these for a Formula 3 car, I saw peaks of 18Nm, with a standard 250mm diameter steering wheel measured with strain gauges at the turn-in phase, dropping off as the racecar goes through the following phases. Calculating the torque produced into tangential force on the steering wheel gives a 15.3kgf at the steering wheel. I suggest you spend 30 minutes practically lying down and lifting 15kg every 30 seconds to give you an appreciation that motor racing is indeed a tough sport.

Even power steering can bring issues, if the system fails, most notably in front-wheel drive cars, where it also has to contend with torque steer. We had a PAS pump failure on the Nissan Primera BTCC Super Touring Car at Snetterton, which resulted in our driver, David Leslie, doing an impromptu Rallycross over ploughed fields as it was physically impossible to turn the car.

Some of the limitations on design to cater for a driver's preferences also surfaced on the Primera. When Laurent Aiello came to drive with us he wanted more assistance on steering, as he was on the small side. In this case we could only give him 30 per cent of what he wanted, as the seals in the rack would not take more than a 100psi pressure, limiting the assistance.

Other items not to neglect are the elbow room needed when on lock (more critical in single seaters), the steering wheel angle to vertical (too much angle will make arms extend and retract with lock, possibly giving unfavourable lever ratios to joints and increasing muscular effort, as well as hitting the ribcage or seat) and even rim thickness, as the hands need to clasp it to put the effort in.

Sitting comfortably

But to steer a car a driver will need somewhere to sit, which brings us back to seats. These must provide maximum support for normal driving situations, and maximum protection and energy absorption in crash situations, using lateral head support, a headrest and good lower and upper body lateral support. Bespoke racing seats are designed for this, and usually FIA certified.

Monocoques allow bespoke foam seats to fit in the tub as well, shaped to the individual driver in the case of endurance cars. Here, each driver has their own shell that goes over the base seat. Incidentally, you should ensure it does not cut circulation under the thighs, as this can lead to cramps in long driving stints.

Foam seats are cast by using expanding polyurethane foam. But today you can laser scan the driver's back to have a personally fitted, CNC-machined seat shell. In the old days, meticulous drivers who knew what they wanted could make several seats during fitting, until satisfied, only to then spend hours rasping away with a file at the foam for a better fit.

The minimal leg well space is recommended by the FIA. One of my habits when designing a racecar is to ensure the leg can swivel around the hip joint and clear the bottom of the dash bulkhead in case of an accident and a major shortening of the footwell. Some regulations actually now require this.

From the seat, while strapped in, you need to make sure all the controls are in comfortable reach of the driver and are easy to operate. Controls that are awkward to reach or difficult to operate will distract the driver and can result in driving mistakes. 100 per cent of the driver's attention should be on driving, at all times.

Brake time

Driving, of course, also includes pushing the pedals. Like the steering wheel, these involve leverage within a limited space. Important factors affecting the pedals include the distance from the driver – given the limited motion of the legs, pedals should be located at a correct distance to ensure they can be used without stretching or applying from a cramped initial position. The driver judges the comfort of the position, but in general the resting angle for the legs should be around 90 degrees, to give enough leverage for long pedal travels.

For shorter travels, or more laid-back seating positions, angles of up to 120 degrees can be considered acceptable.

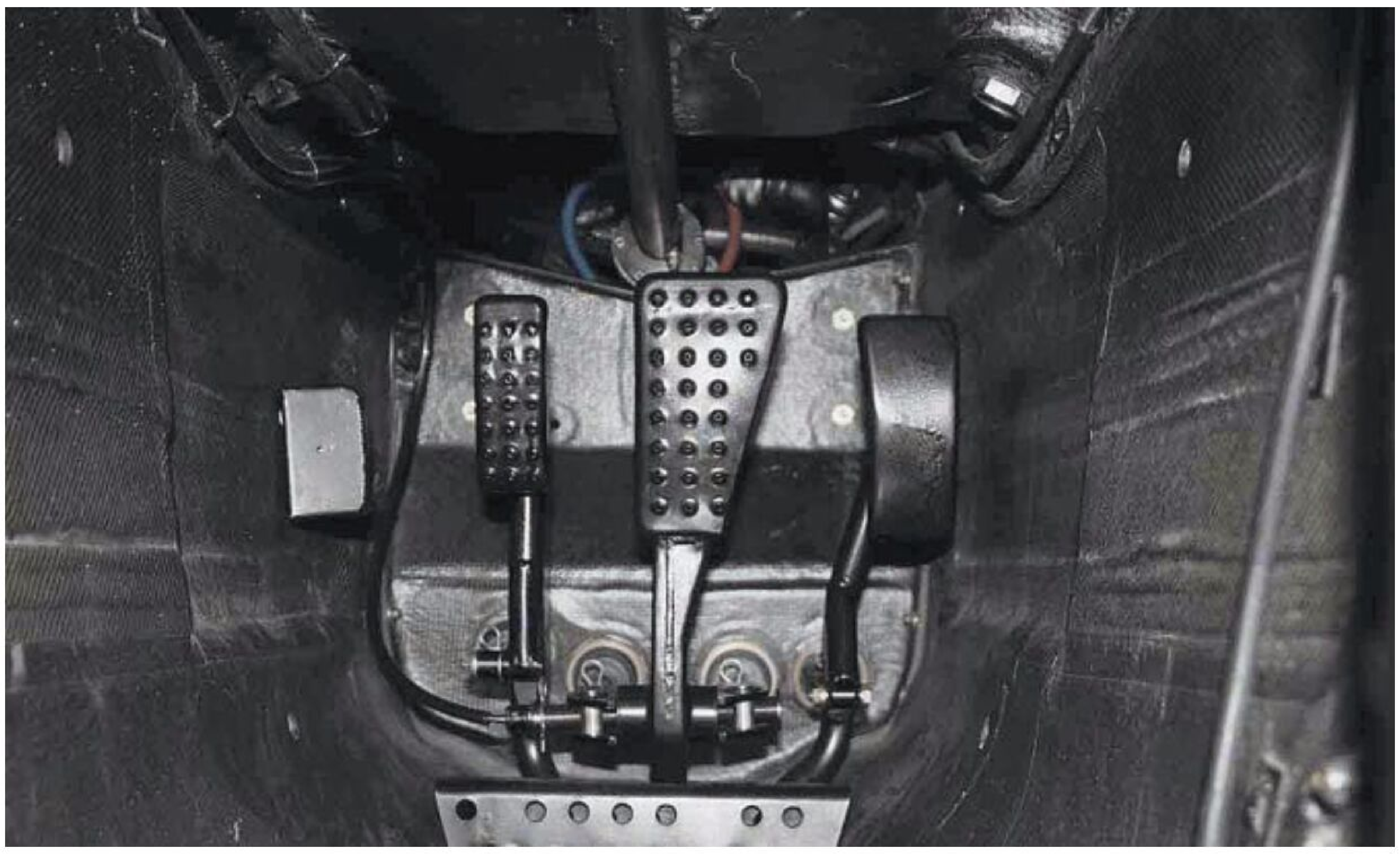
Brake pedal travel is constrained by the force that needs to be applied to give the braking required, the leg travel available and the need to modulate braking. A long travel will be softer and easy to modulate, but can be fatiguing over a long race. Also, as the brake pedal goes down due to wear and heating, the movement needed can go over travel available. This can be embarrassing, and even expensive.

A short travel will demand extra effort and is difficult to modulate. Both cases can be calculated by working backwards from your wheel braking limit, through caliper and disc size, via master cylinder diameters and balance bar position. Fundamentally, juggling with leverage and master cylinder sizes will be fine-tuning, following the basic mechanics of levers. Only power assistance with or without ABS can alter that substantially.

Each individual car design will have to take into account mechanical and hydraulic installation losses. Mountings deflect (this is quite common with pedal and master cylinders), hoses expand (that's why hard lines in certain parts of the run are advisable, for minimal expansion under pressure, unlike flexible hoses) and calipers also expand and hubs deflect under load, not only increasing travel, but also making it non-linear, so harder to modulate.

Clutch and throttle

There are smaller forces needed for the clutch and throttle pedals than the brake, but they are subject to the same sensitivity needs, in order to avoid the 'mousetrap clutch' or an overly sensitive throttle, which as well as being harder to control is subject to unwanted upset over bumps when not against its stops.



Classic pedal set up with brake and throttle optimised for heel and toeing. Note foot rest to the left of the clutch

A 'fourth' pedal, or foot brace for the clutch foot, helps steady the driver, too. Of course it is not required in a two-pedal car with left foot braking and hand clutches on the wheel.

As for the shift lever, or paddles, there are many possible layouts. But they need to be able to be operated without the hand or arm hitting the surroundings. And always remembering that joints and connections stretch and develop play over time, so cater for degradation of mechanical efficiency in the design.

Here are two points to ponder from Lotus design office survival rules: '1. Gearchange linkages wear, bend and stretch. Provide 100 per cent over-travel clearances in all directions. 2. Remember, a frantic driver can put 250lbs [113kg] on a pedal or a gear lever.'

As for paddles, in my experience they have only given me electrical problems, but that, again, is another multi-volume encyclopaedia. Not to be a Luddite, but there is a lot to be said for the magneto 'one active wire' systems, if only on the grounds of reliability.

Switch craft

Toggles and switches also have a multitude of possible layouts. Modern single seaters tend to have most instruments and switches on the steering wheel, but other classes are more varied. Researching existing layouts on the 'net will inform well, just respect ergonomic practice.

The driver receives information through the seat, steering feedback and sound, and additional information that helps optimise the driving comes through instruments. The visibility part of a design will also determine the placing of the gauges, digital readouts or lights. We will not go into the different types of placement, that would take another article. Suffice to say, different classes have steering wheels with dashes, separate dashes, projection on windshield or HUDs, even sonic warnings.

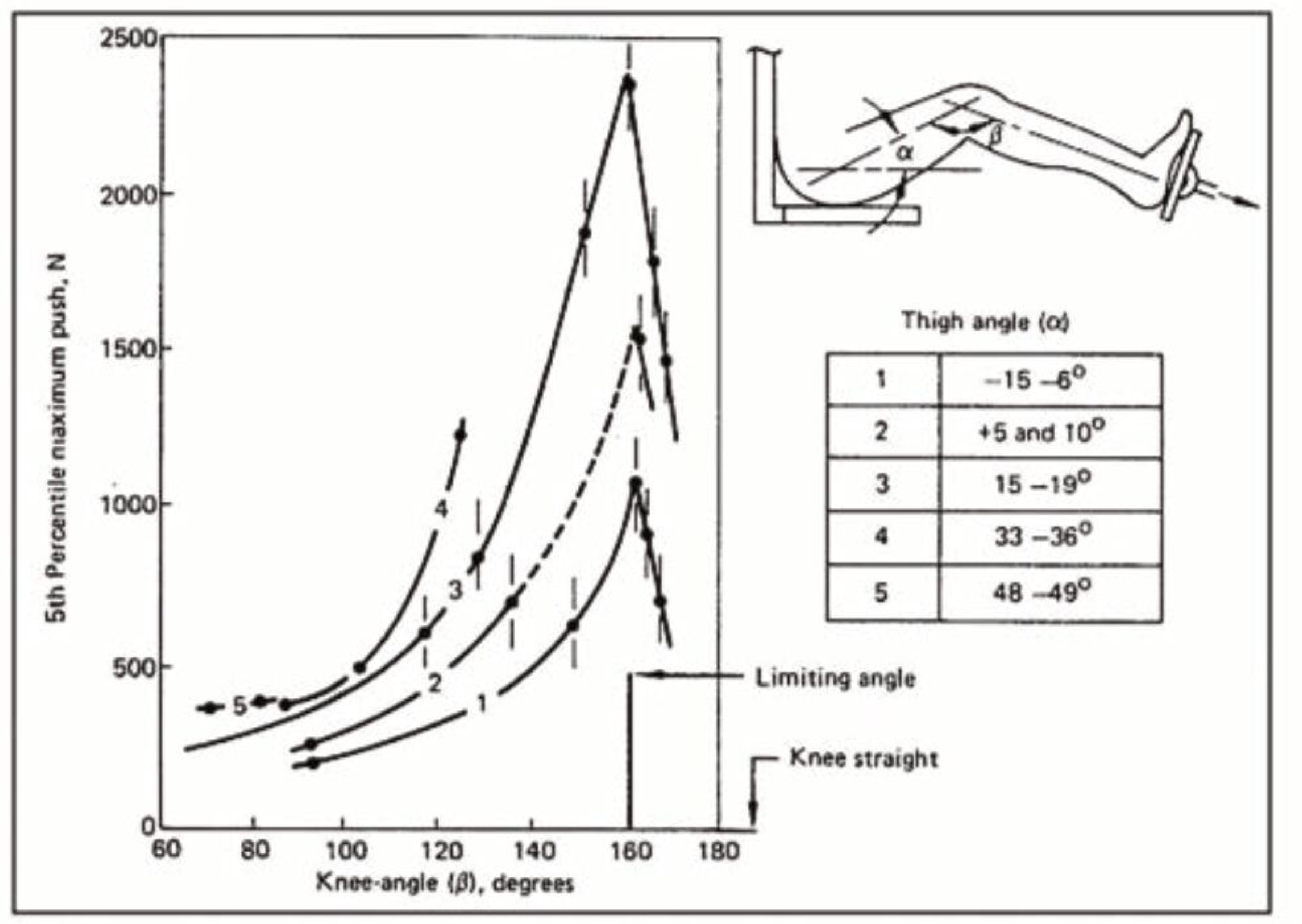
As a rule, looking at this information should not demand the driver take their eyes off the road, so all visual input should be within a 10-degree arc from line of sight.

Also, something that is easily overlooked, driver-to-pit communication is usually catered for by radios, and basically all leads and volume controls should not interfere with the movements of your race driver.

Handling the heat

The cockpit also needs to be a comfortable environment. Yet heat, noise and vibration are all an integral part of racing. The fire retardant race suits, plus fireproof underwear, hold in body heat, and the exertion of driving produces a lot of extra heat. Keeping the driver cool means having fresh air ducted into the cockpit.

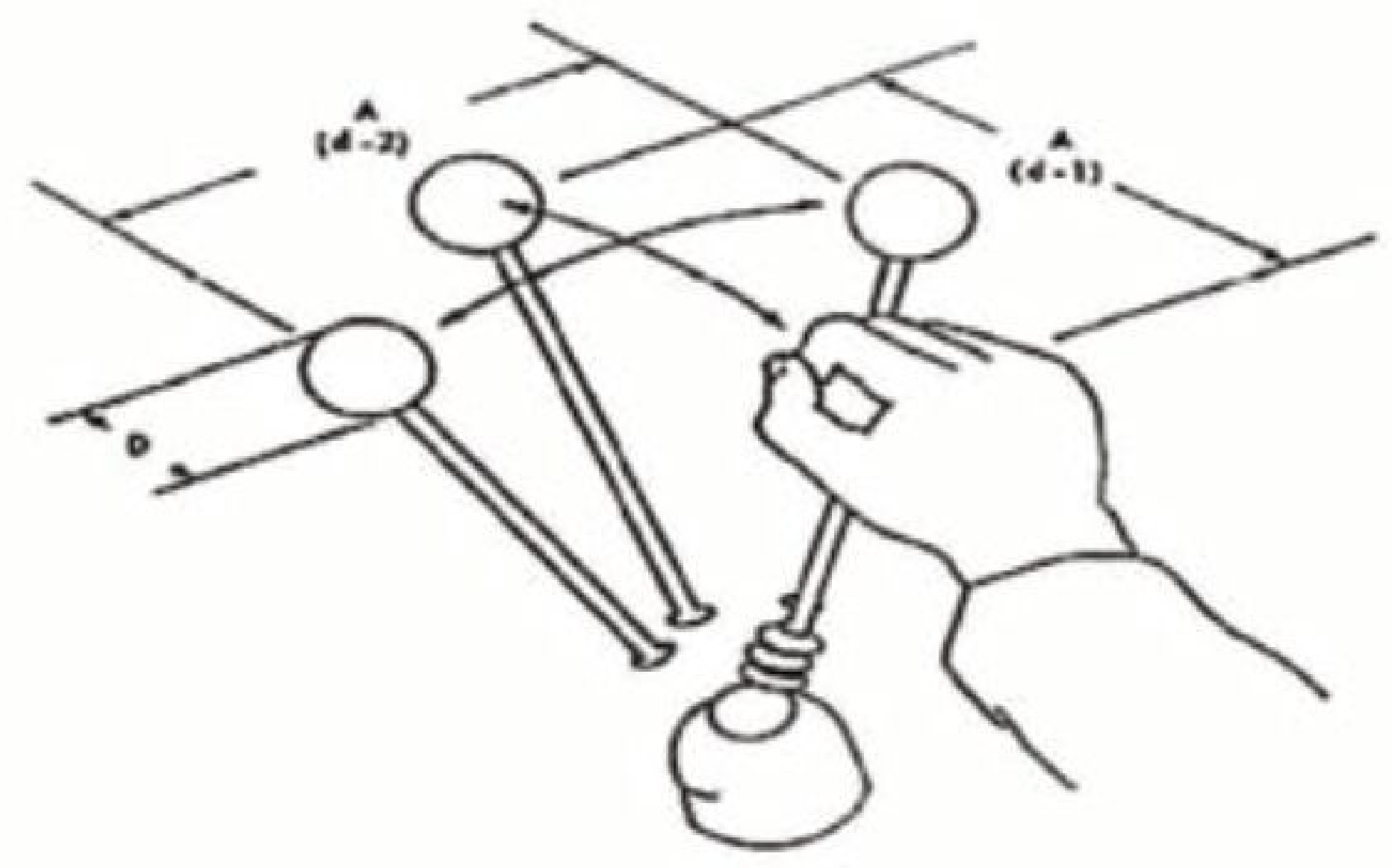
Figure 4.9.3-7 Leg Strength at Various Knee and Thigh Angles (5th Percentile Male Data)



Reference: 1, p. 115; NASA-STD-3000 206

Braking can be a huge physical effort in some racecars so it's vital there is enough room for the leg to bend to achieve the leverage required

NASA's ergonomic data for a typical H-pattern gearstick



	DIAMETER		RESISTANCE			
	D		(d-1)		(d-2)	
	Finger Grasp	Hand Grasp	One Hand	Two Hands	One Hand	Two Hands
Minimum	13 mm (0.5 in.)	38 mm (1.5 in.)	9 N (2 lb)	9 N (2 lb)	9 N (2 lb)	9 N (2 lb)
Maximum	38 mm (1.5 in.)	75 mm (3 in.)	135 N (30 lb)	220 N (50 lb)	90 N (20 lb)	135 N (30 lb)

	DISPLACEMENT		SEPARATION	
	A			
	Forward (d-1)	Lateral (d-2)	One Hand Random	Two Hands Simultaneously
Minimum	-	-	50 mm (2 in.)	75 mm (3 in.)
Preferred			100 mm (4 in.)	125 mm (5 in.)
Maximum	360 mm (14 in.)	970 mm (38 in.)		

As I started out racing in South America, in tropical conditions, this made me routinely engineer cooling into the car as we often raced in ambient temperatures of 40-45degC.

Engine cooling is important, but so is driver cooling. Our best result in Formula 1 at Fittipaldi was second at Rio (Brazil) in 1978, achieved in ambient conditions of 42degC. The car had big scoops on the nose, over the top of the front wing leading directly to driver, plus assorted extra vents and inlets on windscreen and flanks.

Japanese Super GT had additional problems. A front-engine car with side exhaust and, at the time, a steel shell, cockpit heat was a big issue.

Switches and toggles need to be within easy reach of the driver

» Information should not demand the driver take their eyes off the road, so all visual inputs should be within a 10-degree arc from line of sight

MATZZ

www.matzz.at

High Performance Crankshafts, Connecting Rods and Pistons

- **CUSTOMER SPECIFIC CRANKTRAIN ASSEMBLY SOLUTIONS**
- **LIGHTWEIGHT TITANIUM AND STEEL CONNECTING RODS**
- **PREMIUM STEEL AND TITANIUM GRADES**

We look forward to your
queries and discussing
your technical
requirements.

CRANKSHAFTS
MADE IN AUSTRIA
PISTONS & CONRODS

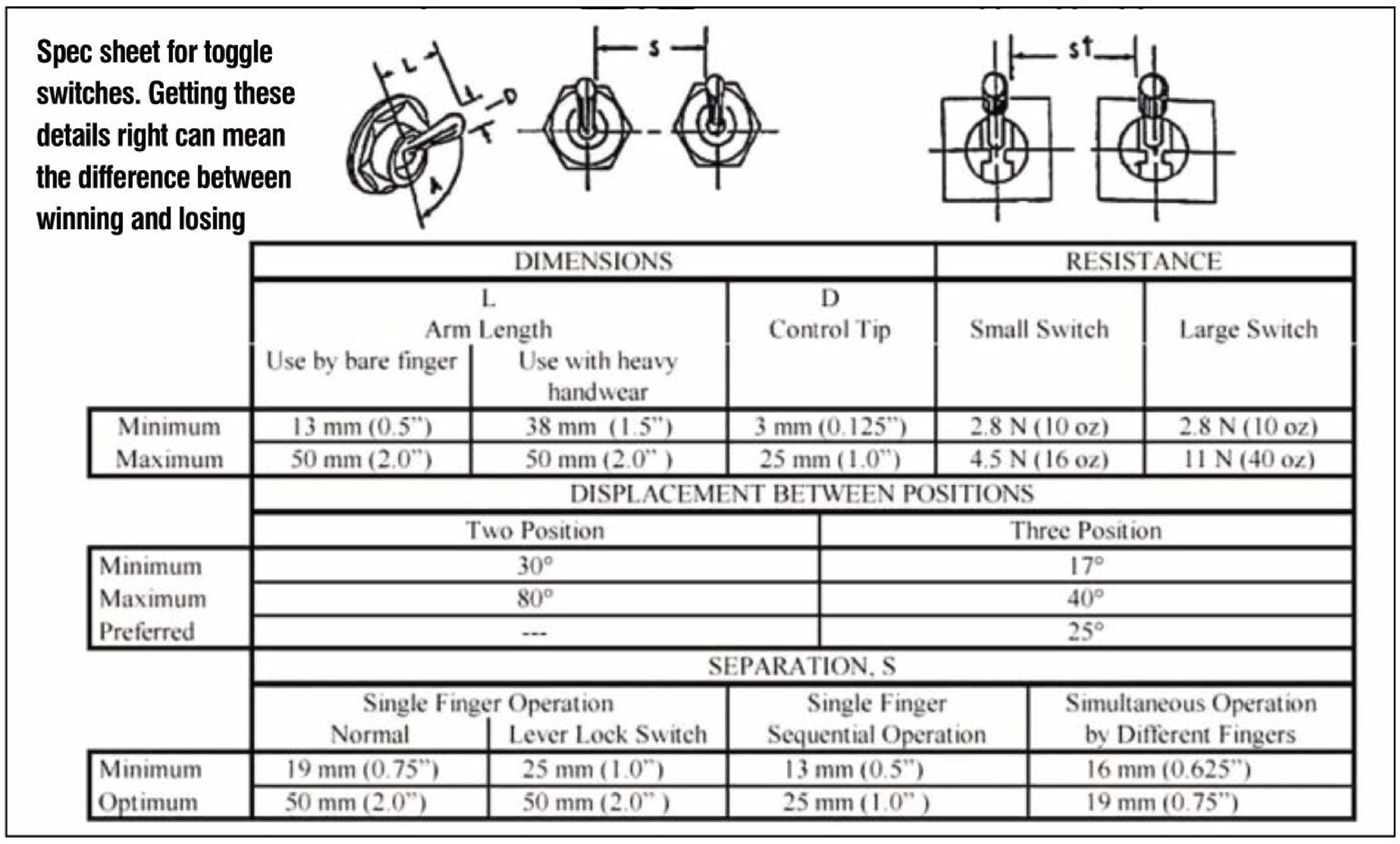
by e-design4all.at

CRANKSHAFTS • CONRODS • PISTONS • PISTON RINGS • BORE COATINGS | www.matzz.at

» Apart from making the drivers comfortable, as engineers you must also account for their safety in the event of an accident

It was bad enough in Japan in summer, but rounds at Sepang (Malaysia) and Buriram (Thailand) took it to new heights, with added humidity to cope with. Using the same concepts from South America, improved with further knowledge, led to a kit applied to the helmet – a transparent shell with sockets to ducting, being blown through openings in helmets developed for open car and motorcycle racing. Further evolutions also ducted air to the seat back. Such systems are now common in Super GT.

Many cars in the higher classes run air conditioning now, but careful and detailed design could achieve the ultimate tweak of lightening – not having it at all.


Spec sheet for toggle switches. Getting these details right can mean the difference between winning and losing

	DIMENSIONS			RESISTANCE	
	L Arm Length Use by bare finger	 Use with heavy handwear	D Control Tip	Small Switch	Large Switch
Minimum	13 mm (0.5")	38 mm (1.5")	3 mm (0.125")	2.8 N (10 oz)	2.8 N (10 oz)
Maximum	50 mm (2.0")	50 mm (2.0")	25 mm (1.0")	4.5 N (16 oz)	11 N (40 oz)

	DISPLACEMENT BETWEEN POSITIONS	
	Two Position	Three Position
Minimum	30°	17°
Maximum	80°	40°
Preferred	---	25°

	SEPARATION, S			
	Single Finger Operation Normal	 Lever Lock Switch	Single Finger Sequential Operation	Simultaneous Operation by Different Fingers
Minimum	19 mm (0.75")	25 mm (1.0")	13 mm (0.5")	16 mm (0.625")
Optimum	50 mm (2.0")	50 mm (2.0")	25 mm (1.0")	19 mm (0.75")

On modern, high-level racecars, most of the readouts and many of the switches are positioned directly on the steering wheel

Safety measures

But now for some more serious matters. Cars are expendable, drivers are not. Apart from making the drivers comfortable, as engineers you must also account for their safety in the event of an accident. Envisaging worse case scenarios is essential here, as not thinking about it can lead to obvious faults in hindsight. To use a cliché 'an ounce of prevention is worth a ton of cure'.

Some major accidents, such as the loss of Senna and Roland Ratzenberger at the San Marino Grand Prix in Imola in 1994, brought in major changes in safety regulations, but we all know there will always be dangers that are extremely difficult to foresee, and sometimes the forces involved end up being too strong to survive. Nevertheless, you can never do too much to mitigate accident effects. You, the engineer, are ultimately responsible.

There are some points that really need to be stressed here. Seat mounts in the case of GTs or Touring Cars need to have mountings engineered to maintain integrity and position at 100*g* impacts at least, when an 80kg driver will represent an eight-tonne load on mountings. The same goes for belt mountings, the standards for these are defined under Standard 8853/98, FIA Safety Harnesses Standard.

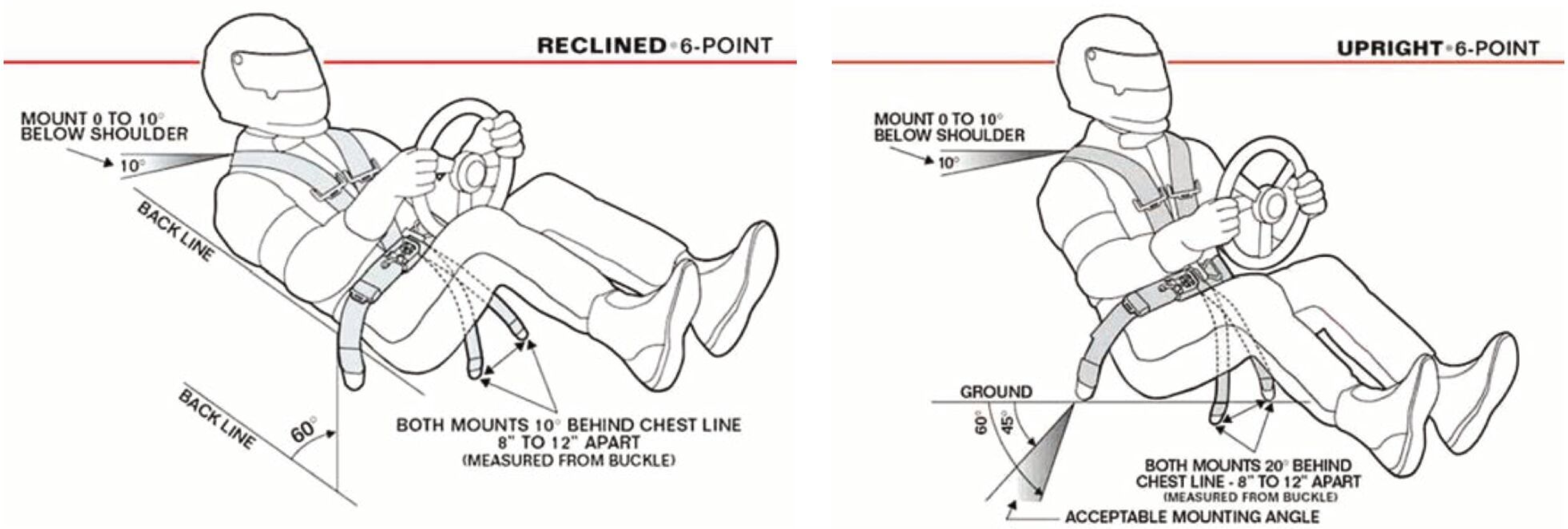
The harness must also have two separate labels sewn on stating the standard the harness complies to and its manufacturing date. A harness has a maximum five-year life before it has to be replaced. The standards define the permissible belt widths and load capacity.

You also need to make sure the belts are attached to a solid structure. When Gilles Villeneuve was thrown out of his car during his fatal accident at Zolder in 1982 his belts held, but pulled out the complete seat bulkhead.

I mentioned earlier the PAS failure incident at Snetterton. Another lesson learned there was that despite having side support and padding beside the legs, the violent bucking motion running over the furrows made the driver's legs flail in the footwell, luckily causing no fractures,

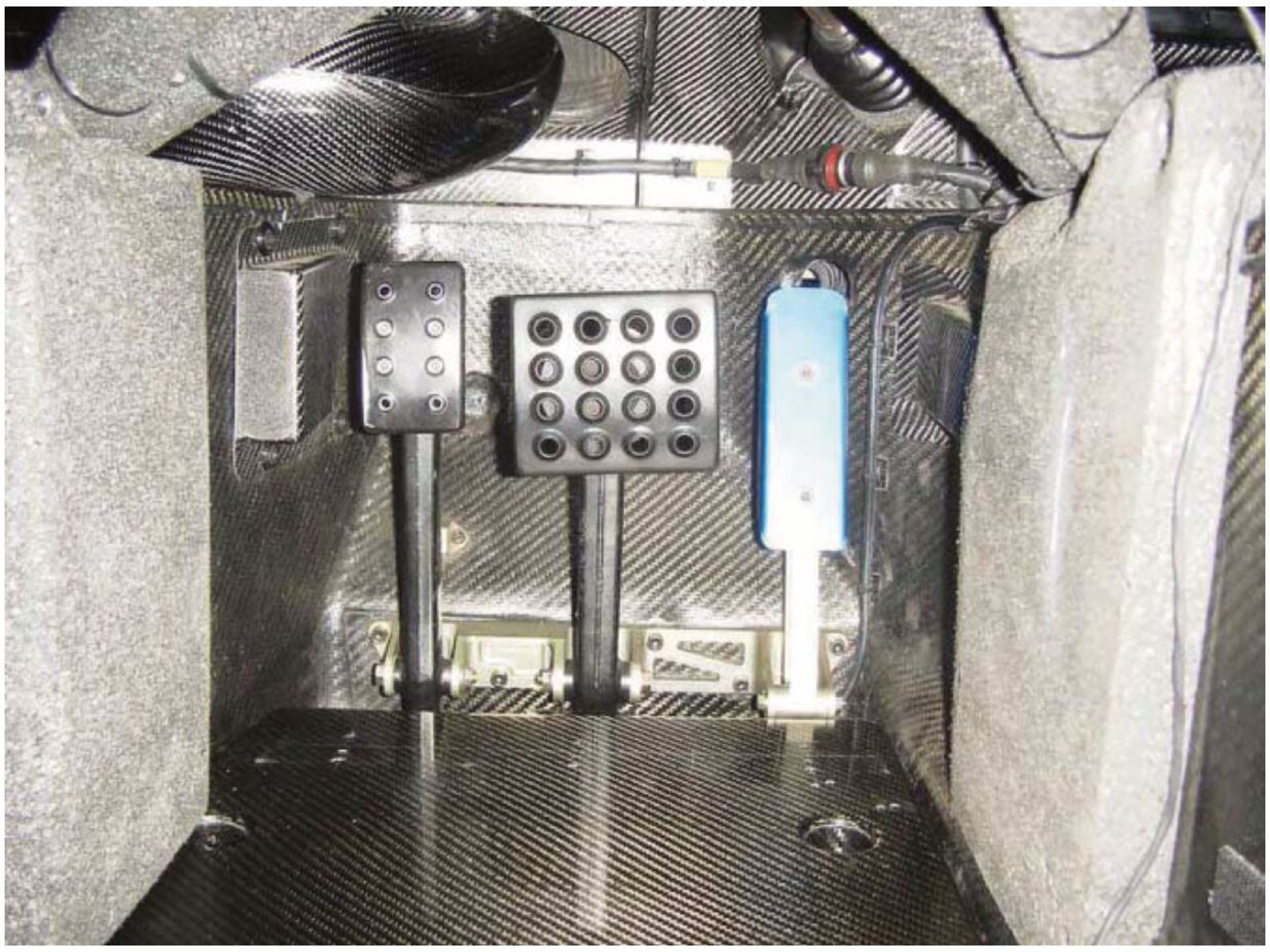

Emerson Fittipaldi finished second at the 1978 Brazilian GP with the help of some Divila-inspired cooling mods


This approach to keeping the driver cool was adopted in Super GT



The FIA's recommended angles for seatbelts for reclining (single seater and Sports Prototype) and upright (Touring Car and GT) seating positions

> **» Part of the safety drive is to ensure there is no intrusion from suspension components**



The padding in the footwell of the Nissan Super Touring Car was to protect the driver's legs during accidents

This survival cell fitted into the DTM spaceframe

Cockpit padding is a simple, cheap, highly effective safety measure

but making his racing the following week questionable because of shin injuries.

From that point onwards we had the leg area fully shielded with additional panels to protect legs in all directions. Team Rosberg, which ran Nissan's Super Tourers in the German Touring Car Championship, went a step further in DTM, designing and producing a survival cell to be fitted to its DTM spaceframe at the time. It was a carbon monocoque, protecting the driver from any intrusion of rollcage or components.

Intrusion protection

In single seaters, part of the safety drive is to ensure there is no intrusion from suspension components, the lower legs of front wishbones being especially at fault here, and several such incidents have been recorded over the years. Some racing categories now actually specify anti-intrusion measures in the regulations.

Usually forgotten and innocuous components can cause trouble, too. Benoit Treluyer had one of the biggest accidents in any car I have run, a major shunt that broke the engine / gearbox / rear suspension unit off when hitting the Armco, with the tub tumbling down the road before stopping. Roll hoops, deformable structures, padding and HANS protected him correctly, but the battery, even though it was well strapped down and appropriately restrained, allowed acid to spill in the gyrations and gave him electrolyte acid burns. Despite decades of racing, that was a factor I had admittedly never considered before.

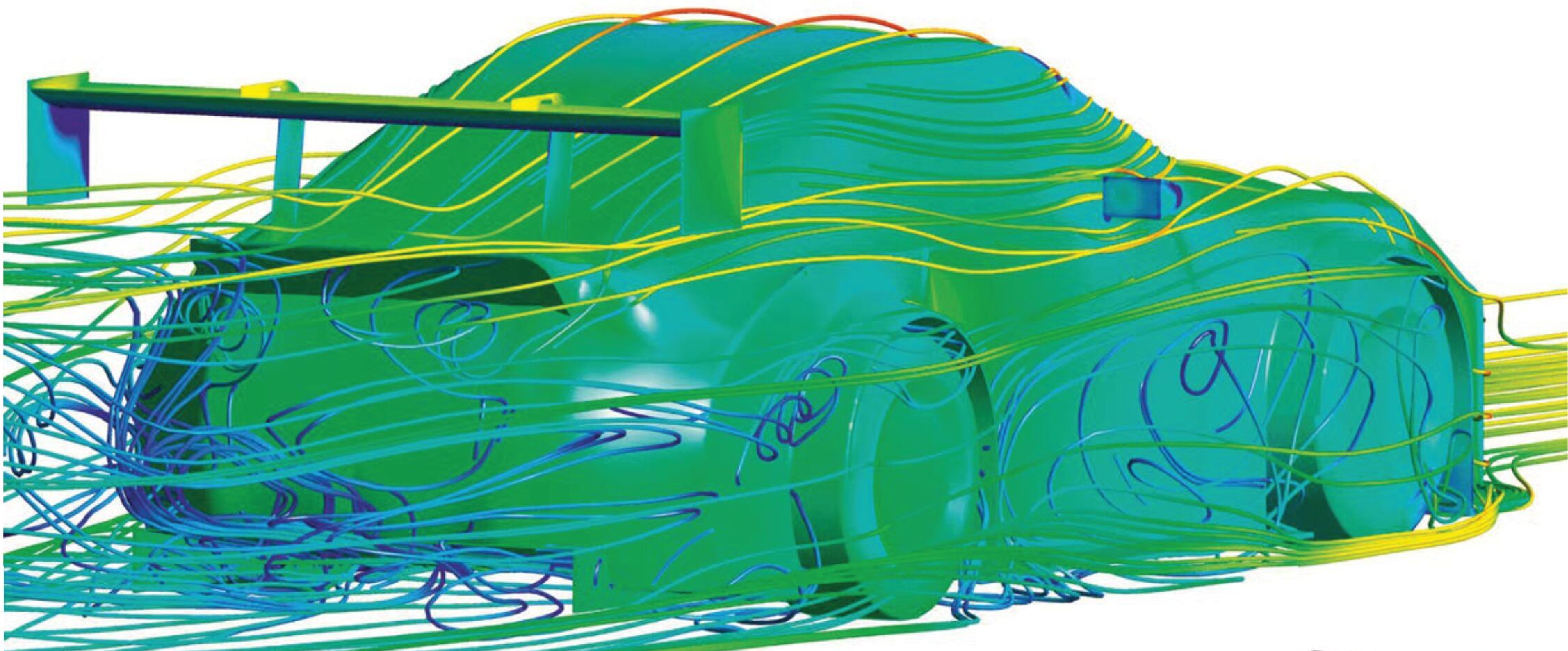
I will finish this article with the following caveat: not all of these actions are required in all formulae. Each class of racing generates its own demands, excepting the safety ones, most of which are regulated and cover the basics well. In fact, it is very informative to read all the different sanctioning organisations' rules regardless.

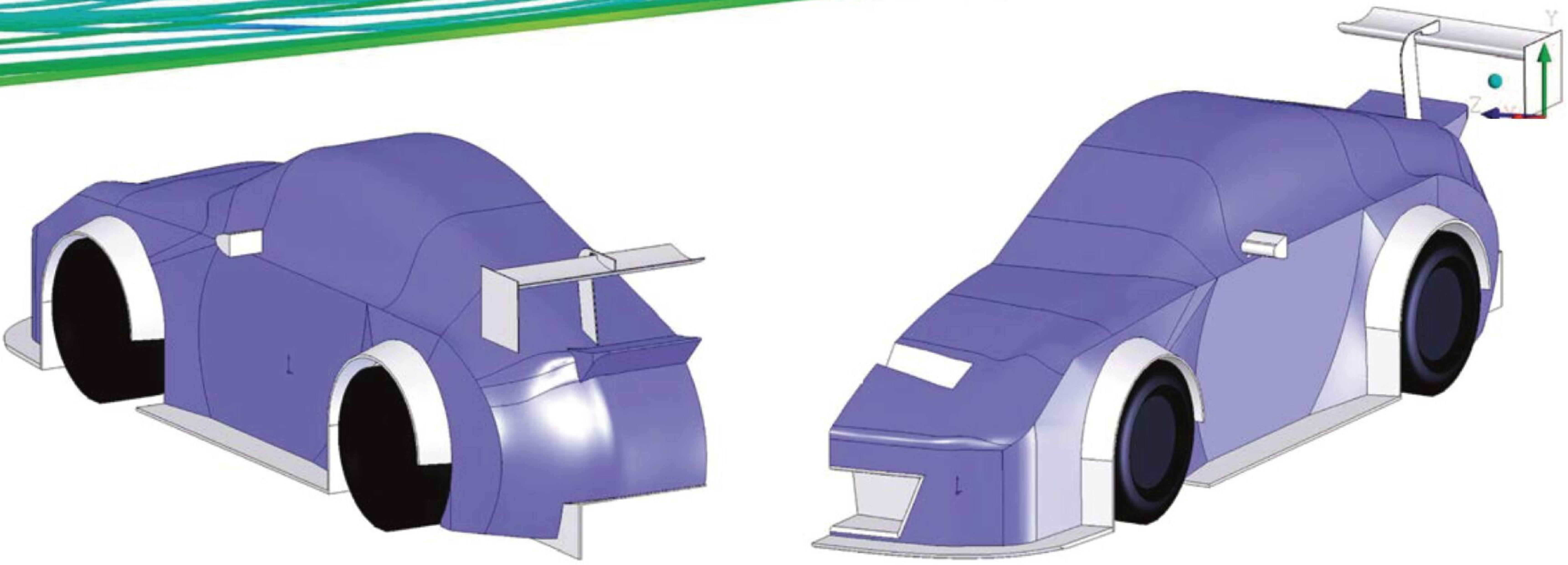
If this helps your design avoid one injury I will be happy. My proudest boast from my racing career is that in the course of over 2000 races over 60 years and uncountable accidents, the only injury of note for any of my drivers was a broken thumb – which occurred when he caught it in the mesh catch fencing. A lot of luck, yes, but also a lot of forethought.

GT aero: the basics

With restrictive rules and large body shapes, GT cars are a challenge for aerodynamicists. CFD may be used to understand the inherent features of these racecars

By Simon McBeath





CAD 1: The generic GT model used for our aero studies

It is true to say that full-scale wind tunnel sessions generally produce as many questions as answers. This can be for many reasons, sometimes because it is the first time a car has been aerodynamically investigated, or just because there isn't time to examine everything on lengthy wish lists. Some modifications are just not practical to carry out in a relatively short wind tunnel session.

The key to maximising the benefit of time in the wind tunnel is to run through a slick programme of easy adjustments to gain the maximum knowledge from those precious few hours. So it's useful to be able to bring other tools to the party in order to examine aspects that cannot be covered in the wind tunnel. ANSYS CFD is the tool in question here, and in this article we turn our attention to some of the basics of GT aerodynamics using a simplified CAD model of a generic GT racecar.

The process started by working up a set of suitable CFD parameters that generated solutions in a sensible time frame and to an acceptable level of fidelity. It's fair to state at the outset that these are not high-level simulations. The model is simplified, the resources for performing CFD are basic, and the absolute results should be treated with a pinch of salt. The primary purpose here was to investigate the effects of fairly broad brush configuration changes to see what trends and responses emerged.

Having said that, it was gratifying that the aerodynamic coefficients that arose on our GT model were not far from those of actual GT cars we have evaluated in the MIRA full-scale wind

Table 1: Aerodynamic data on our CFD model and the Porsche 997 GT2 and Ferrari F430 in the wind tunnel

	CD	-CL	-CLfront	-CLrear	% front	-L/D
CFD GT starting	0.47	0.83	0.20	0.64	23.9%	1.84
CFD GT baseline	0.46	0.85	0.33	0.52	38.8%	1.87
997 starting	0.435	0.523	0.110	0.413	21.1%	1.203
997 optimised	0.439	0.705	0.245	0.460	34.8%	1.606
F430	0.523	0.805	0.317	0.487	39.4%	1.539

Sources of downforce and lift

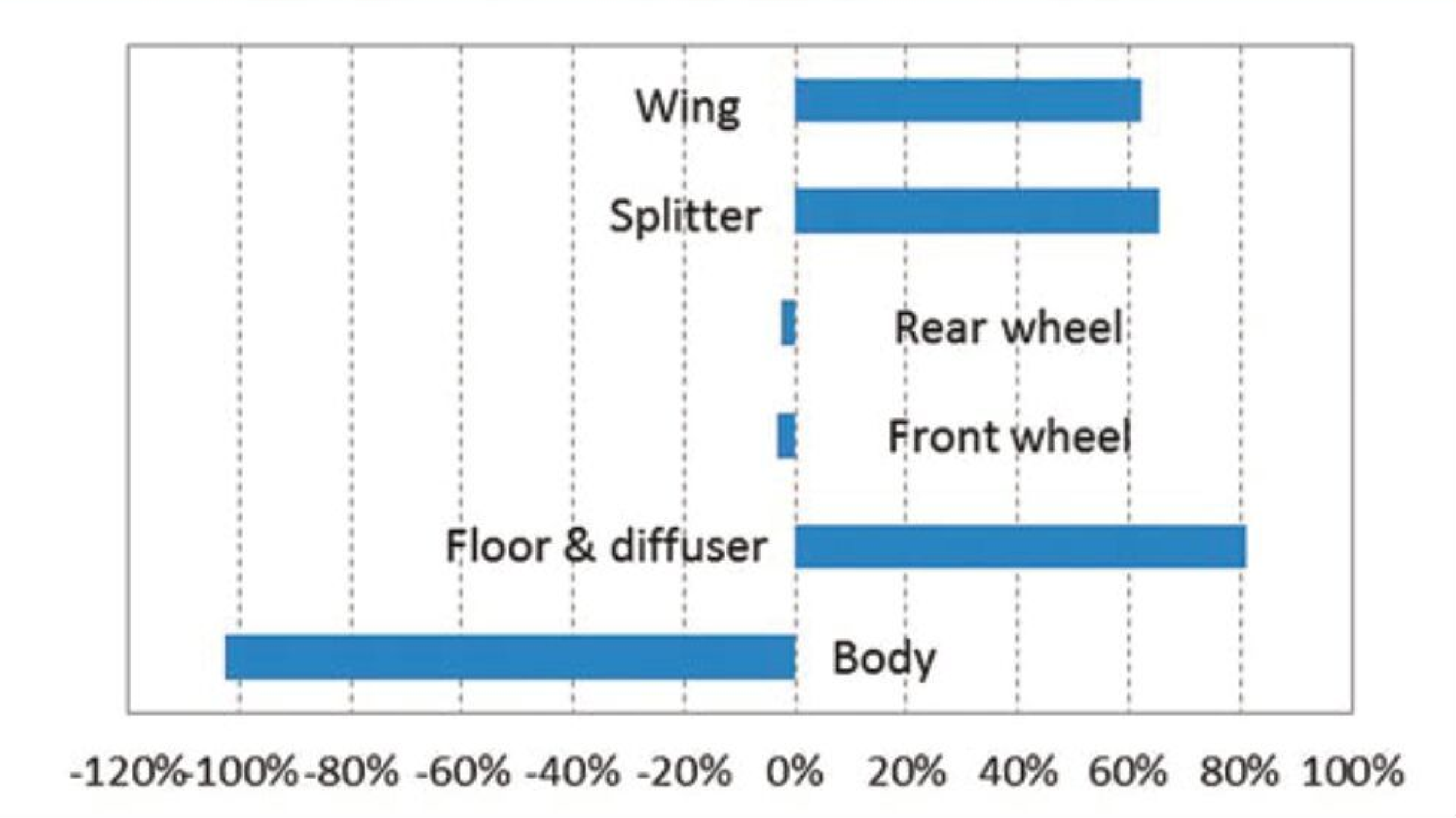


Figure 2: The lift and downforce contributions of the major components on our model

Sources of drag

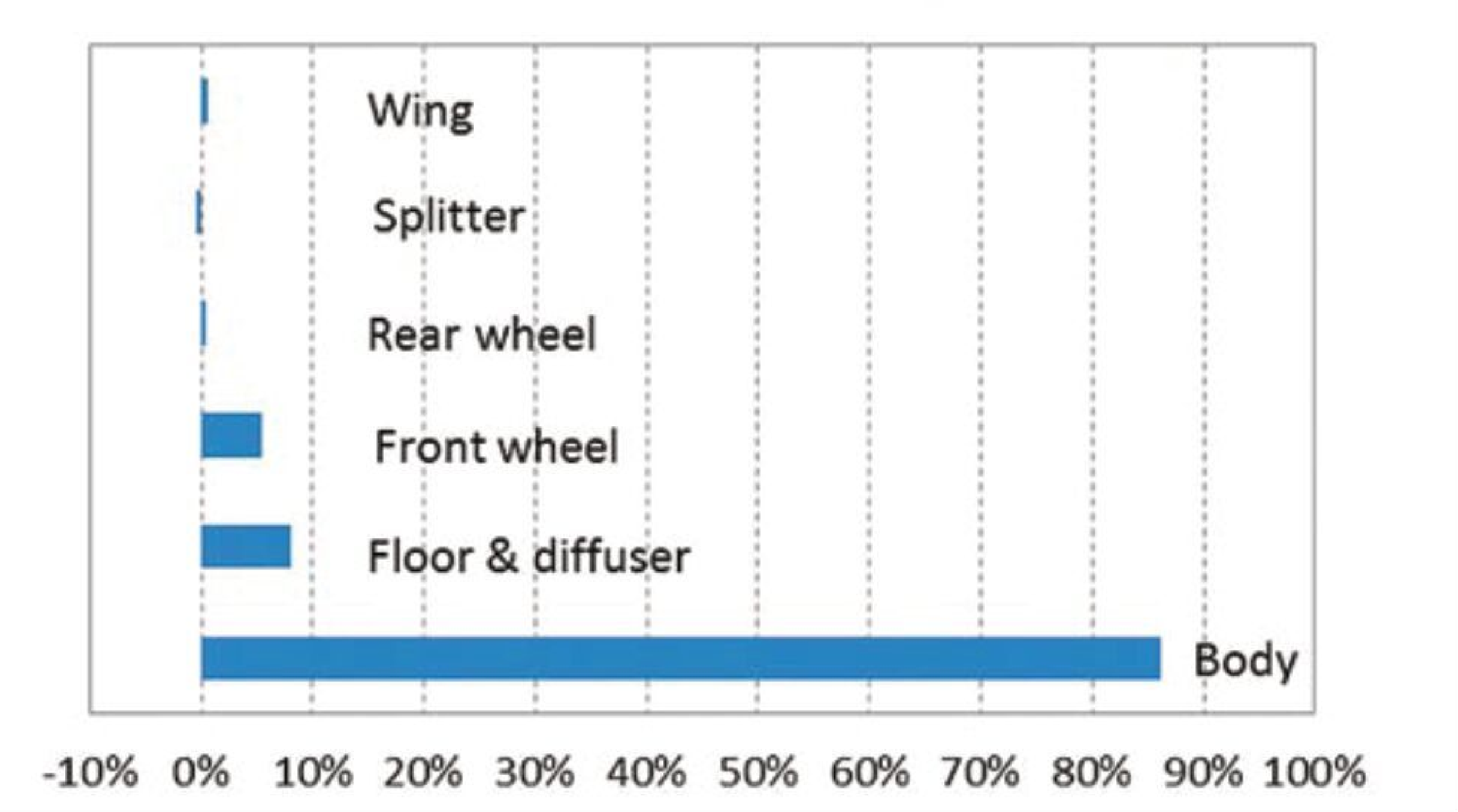


Figure 1: The drag contributions of the major components. The main source is obvious

> » The first run showed the front-to-rear aero balance to be just 24 per cent front, some way short of the initial target of around 40 per cent

tunnel facility in the past, and we are going to assume that was not entirely a happy coincidence.

The baseline

While working up the CFD parameters, adjustments were also made to the CAD model so a suitably balanced baseline was created. The starting configuration was actually based on a client's wing positioning study but, as that featured a different design of wing, it proved necessary to carry out wing relocation and angle adjustments, plus some rake variations to achieve a reasonable balance.

The starting aerodynamic package featured a simple, 150mm flat splitter leading to a flat underside. This in turn fed a basic rear diffuser with the transition in line with the rear axle, a roof angle of 12 degrees, two pairs of fore / aft strakes and a termination in line with the rear body. Initial ground clearance was 60mm front and rear, measured at the splitter / floor join at the front, and at the diffuser transition at the rear. The splitter underside was 5mm lower than the main floor.

The single-element wing was almost full car width and one of the writer's own high-downforce, single-element profiles, with a 300mm chord. Initial angle was six degrees and it was set at roof height +40mm, with its trailing edge overhung by 175mm behind the rearmost line of the body.

The first run showed the front-to-rear aerodynamic balance to be just 24 per cent front. That is to say, the proportion of total downforce on the front was 24 per cent, some way short of the initial target of around 40 per cent front. Incremental adjustments were made to reduce the wing's angle to two degrees and to lower it to 40mm below maximum roof height and then forwards by 175mm so its trailing edge was level with the car's rear body. This yielded an improved balance of 28 per cent front.

Finally, rake adjustments were made that lowered the splitter leading edge underside to 47mm ground clearance, kept the front ride height at 60mm but increased the rear ride height to 75mm (equating to 15mm rake on the flat floor), and the diffuser strakes were removed (see **CAD 1**). This brought the balance to around 39 per cent front, which was considered a suitable baseline to work from.

We will revisit the effects of all these adjustment parameters in more detail later. The purpose at this stage was just to achieve a balanced set-up, but nevertheless it was illuminating to see how the model responded to these early adjustments.

The aerodynamic coefficients of our starting and our 'refined' baseline configuration are given in **Table 1**, along with some comparisons with the Paragon Porsche ALMS GT2 997 GT3RSR and MTECH Ferrari F430 Scuderia GT3 that we wind tunnel tested in 2010. Particularly relevant is the Ferrari, which had a similar balance to our baseline CFD model.

Note that coefficients have been given to just two significant figures on the CFD model. This is because, although the CFD solver was run in each case until the forces on the major components were deemed steady, there was a margin of error of up to +/-2.5 per cent in some cases, and without time-averaged data sampling, as is done in the wind tunnel, the third decimal place was thought frivolous.

That said, the drag of our model was in between the real 997 and F430. Downforce was somewhat higher than both real cars, which could be due in part to the wind tunnel's fixed floor suppressing underbody downforce, whereas the CFD simulations included moving ground and rotating wheels, and in part to the CFD model's simpler and essentially flaw-free shape. Real cars have panel gaps, door handles, seams, joins and all manner of inherent defects that compromise aerodynamic performance, whereas our simple CFD model is relatively 'clean'.

The values, however, are comparable to the real cars, which gave some validity to the process, even if our main aim was just to examine the effects of changes.

Aerodynamic forces

It's worth pausing at this point to look at the data and visualisations from this baseline model in more detail, to get an idea of how and where the aerodynamic forces were generated. Looking at **Figure 1**, it's very apparent what the main source of drag was, but that's not at all surprising when the car body is the biggest 'component' of the model and constitutes most of the frontal area.

The floor and diffuser (which were analysed as one component) and the front wheels produced the majority of the rest of the drag, while the rear wheels, the rear wing and the splitter made very small drag contributions. The splitter's essentially negligible drag contribution bears out wind

> » The drag of our model was in between the real [Porsche] 997 and [Ferrari] F430. Downforce was somewhat higher than both real cars

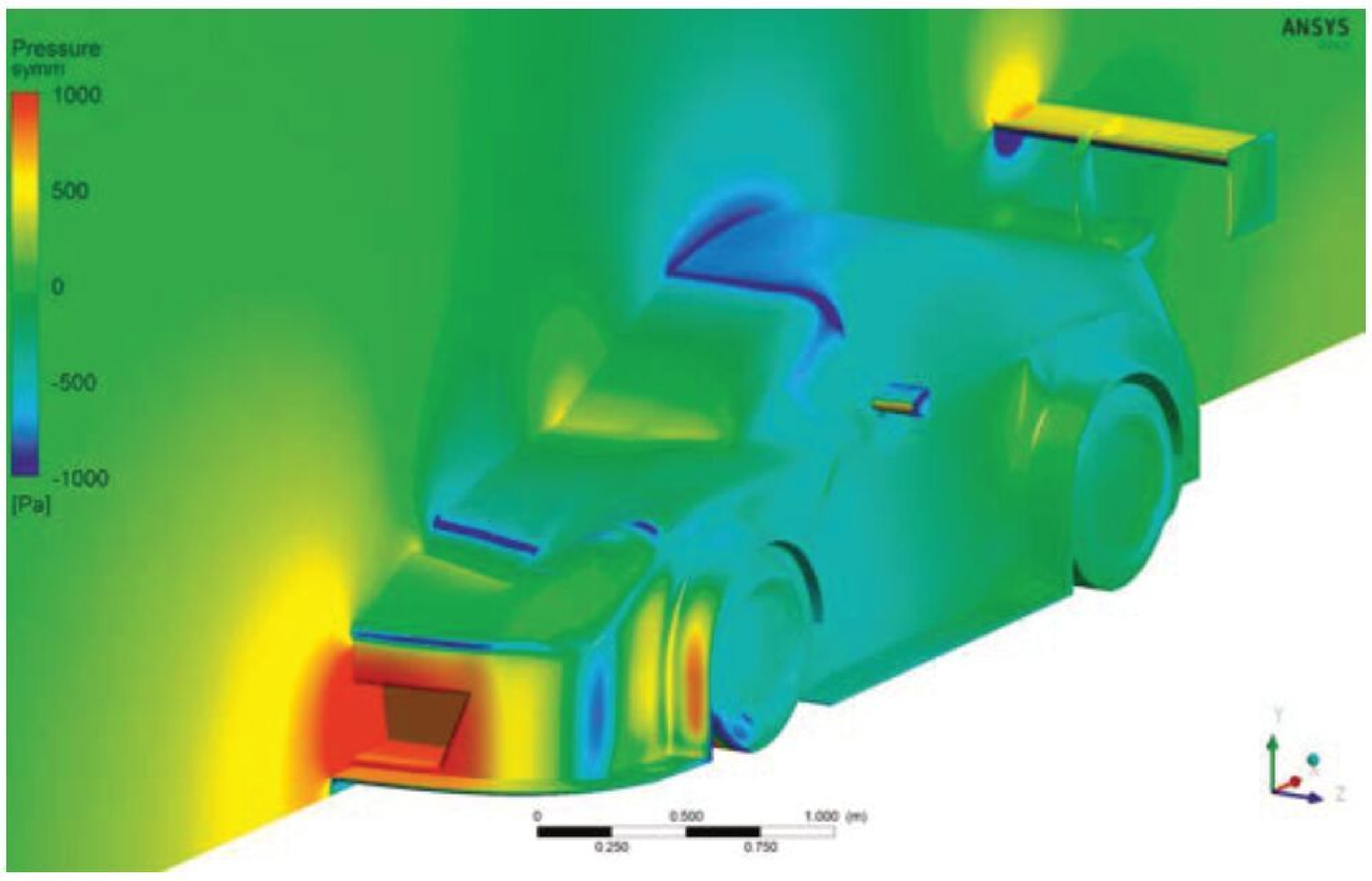


Figure 3

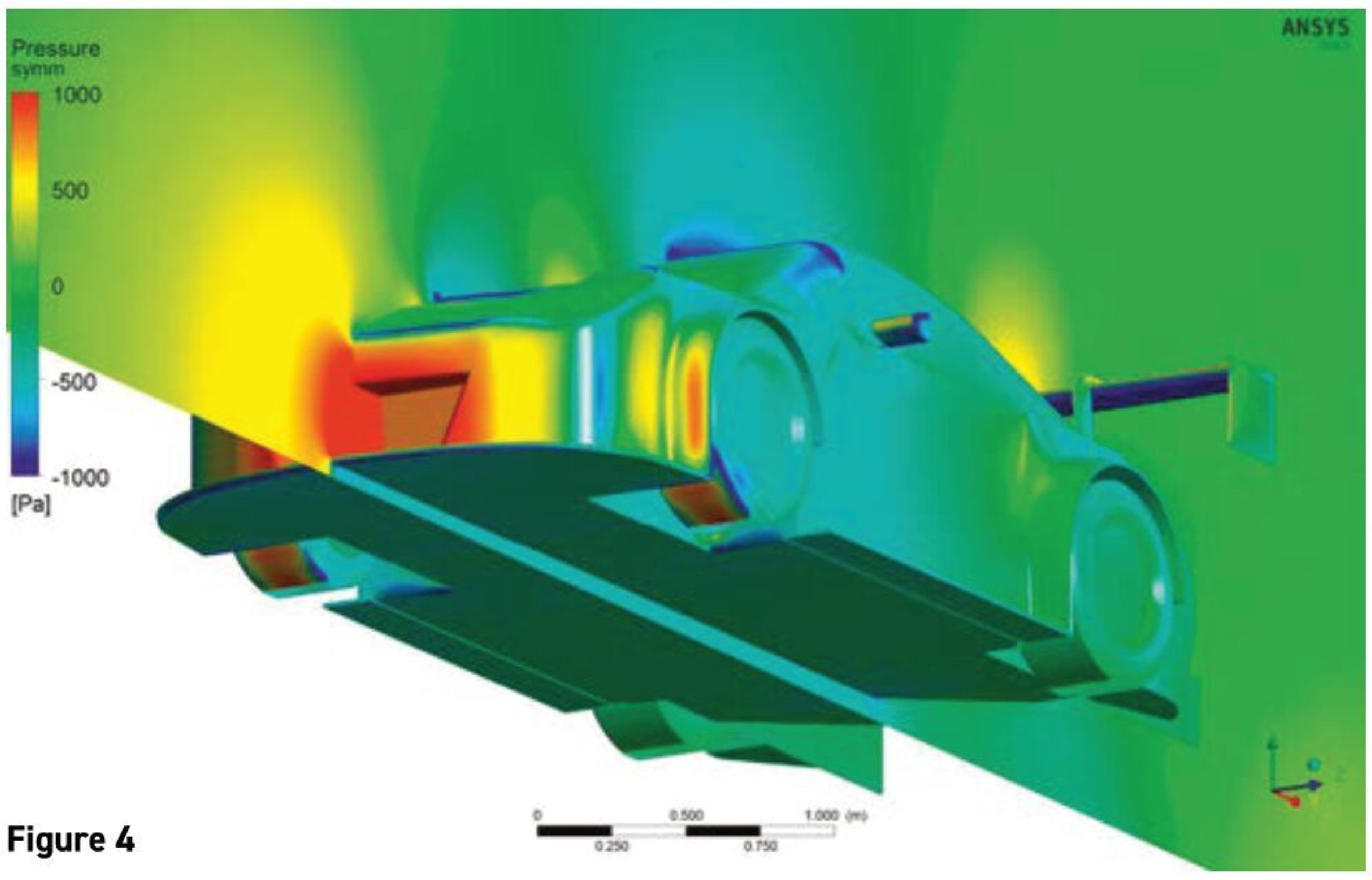


Figure 4

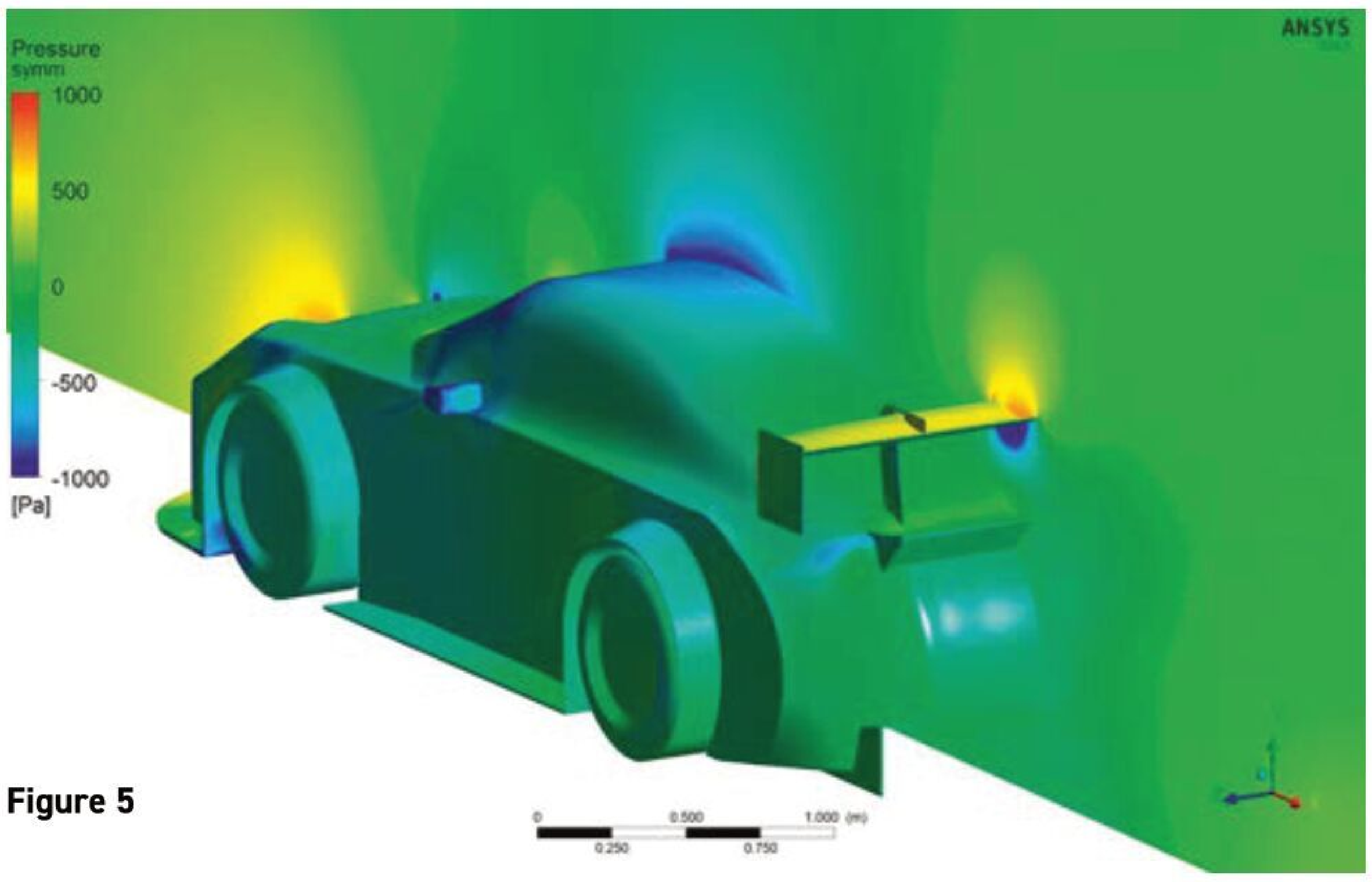


Figure 5

Figures 3, 4 and 5: The sources of drag, downforce and lift are evident from the pressure distributions. High pressure is red to yellow and low pressure green to blue

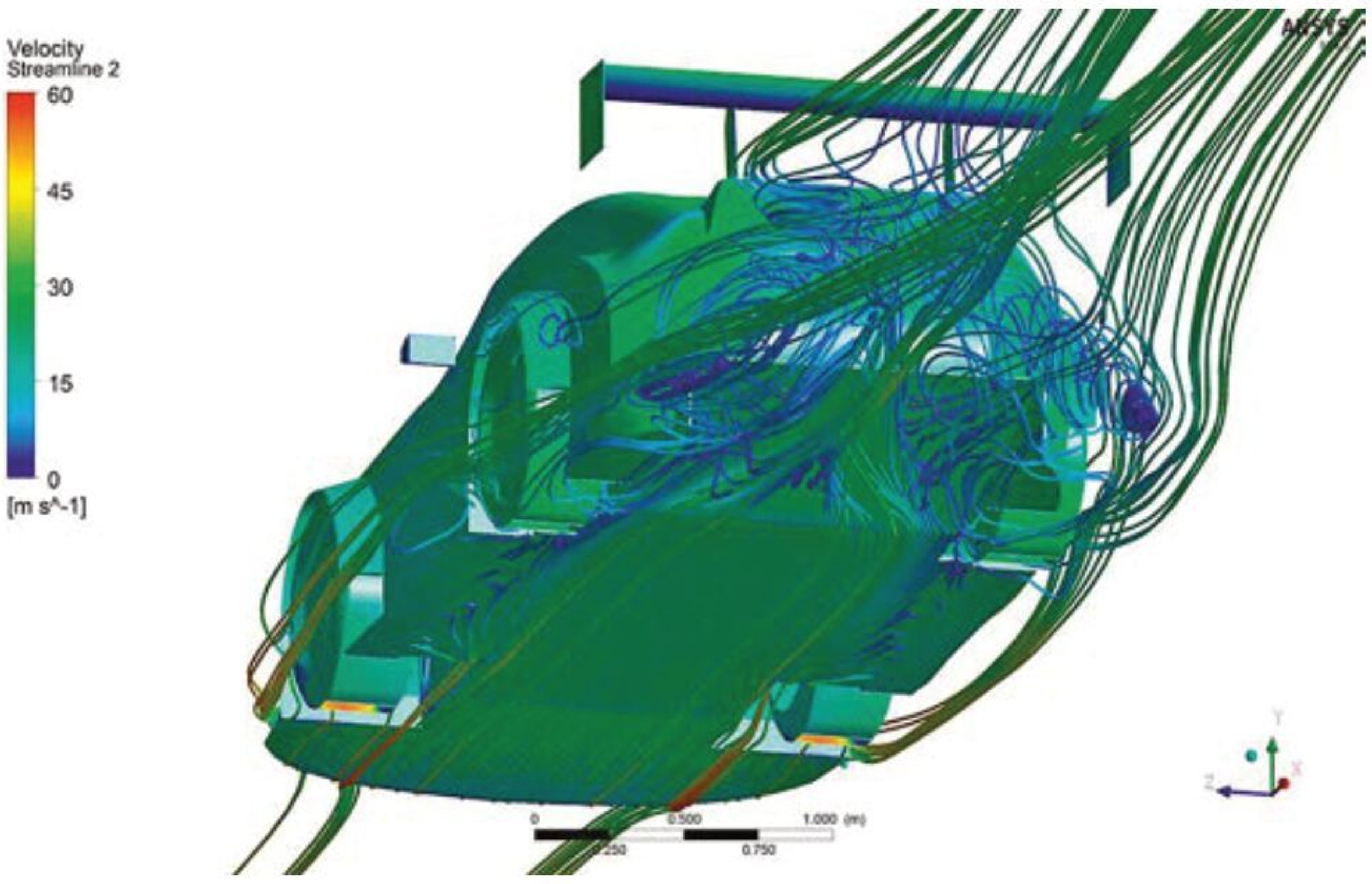


Figure 6: The streamlines reveal that the diffuser was almost stalling in the centre. Also, note that the streamlines in the outer sections of the diffuser appear to be disorganised

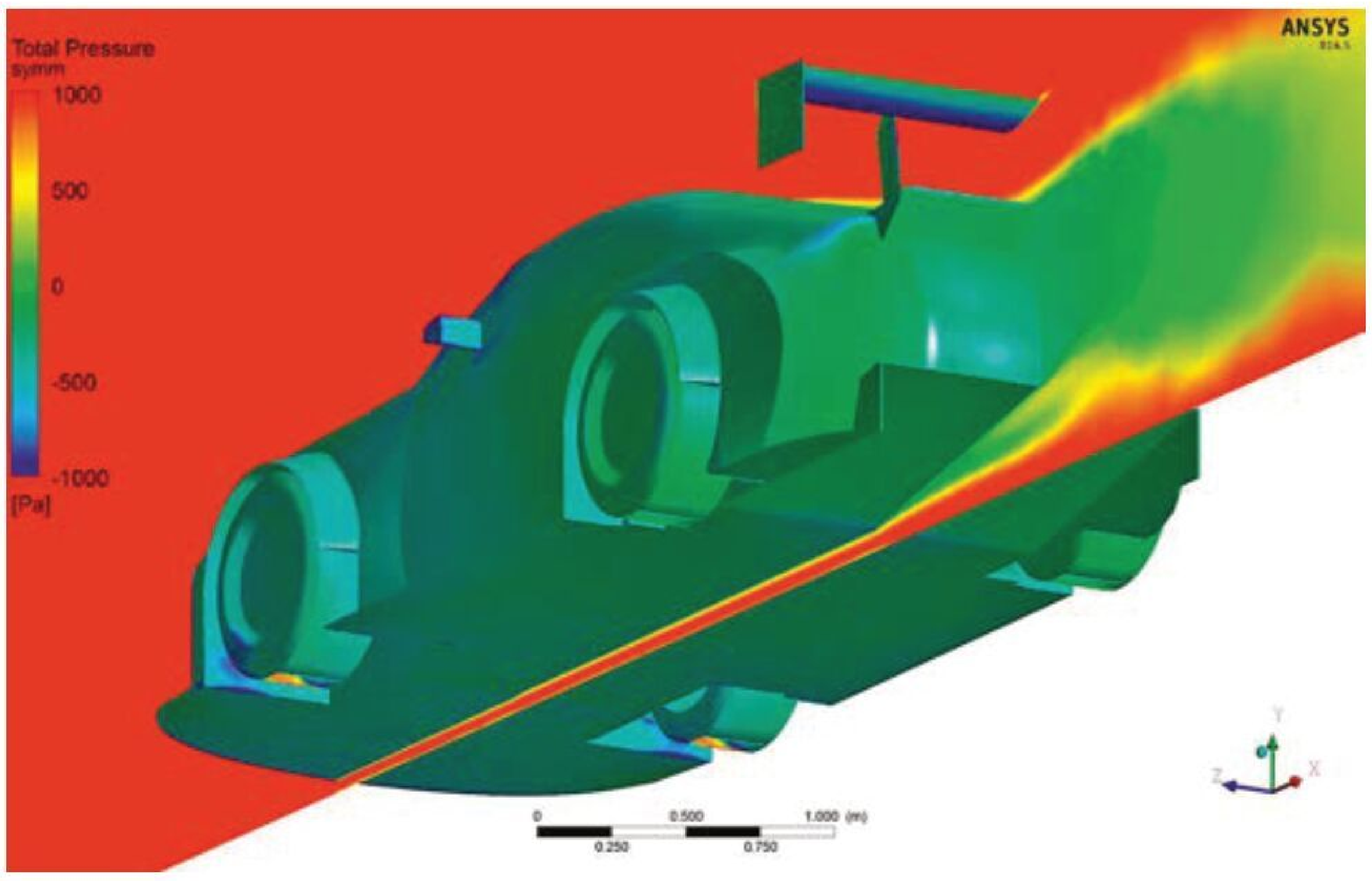


Figure 7: The total pressure plot on the symmetry plane of our GT racecar model shows energy losses in the diffuser centre, which indicates near-stall conditions

Table 2: The effects of reducing diffuser angle

Diffuser angle	CD	-CL	-CLfront	-CLrear	% front	-L/D
12deg (baseline)	0.46	0.85	0.33	0.52	38.8%	1.87
10deg	0.46	0.85	0.34	0.51	39.5%	1.87
8deg	0.45	0.91	0.36	0.55	39.1%	2.01
6deg	0.45	0.89	0.34	0.55	38.5%	2.00
4deg	0.45	0.89	0.35	0.54	39.2%	1.99

tunnel findings that show little, if any, drag change when, say, a bigger splitter is fitted.

Figure 2 shows the sources of downforce and lift on the model. Here we see the wing, splitter, floor and diffuser were the downforce generators, offsetting and reversing the lift generated by the body and, to a much smaller extent, the wheels. **Figures 3-5** show the surface pressures on the model's surfaces and on the symmetry plane, with the pressure range set to emphasise the areas of high pressure (red to yellow) and low pressure (green to blue).

» The key lesson here is that it's unwise to make assumptions about any variable

It isn't particularly hard to pick out where lift, downforce and drag respectively were generated, both on and off the model's surfaces.

Note that the floor and diffuser generated around 39 per cent of the actual downforce, compared to 31 per cent from the splitter and 30 per cent from the rear wing. The floor and diffuser contribution therefore falls short of equalling and reversing the lift contribution from the body in this specific configuration. Clearly, without the splitter and the wing, the car body's lift would have been the dominant vertical force.

So, having established a balanced baseline model, we then moved on to examine the effects of incremental changes to the key parameters.

There were various aspects of the underbody and diffuser that needed investigating, among which were ground clearance, rake and pitch angle. But before that, the diffuser angle was examined. At 12 degrees on the baseline model, it appeared from views of the streamlines, and of the total pressure on the symmetry plane, that the diffuser was partially stalling in the centre, just aft of the transition from the flat floor (see **Figures 6** and **7**). So a set of successively lower diffuser angles was run to enable the data and the visualisations to be examined. **Table 2** shows the results.

Interestingly, the responses to changing diffuser angle were not strong but, nevertheless, there did seem to be a gentle peak in

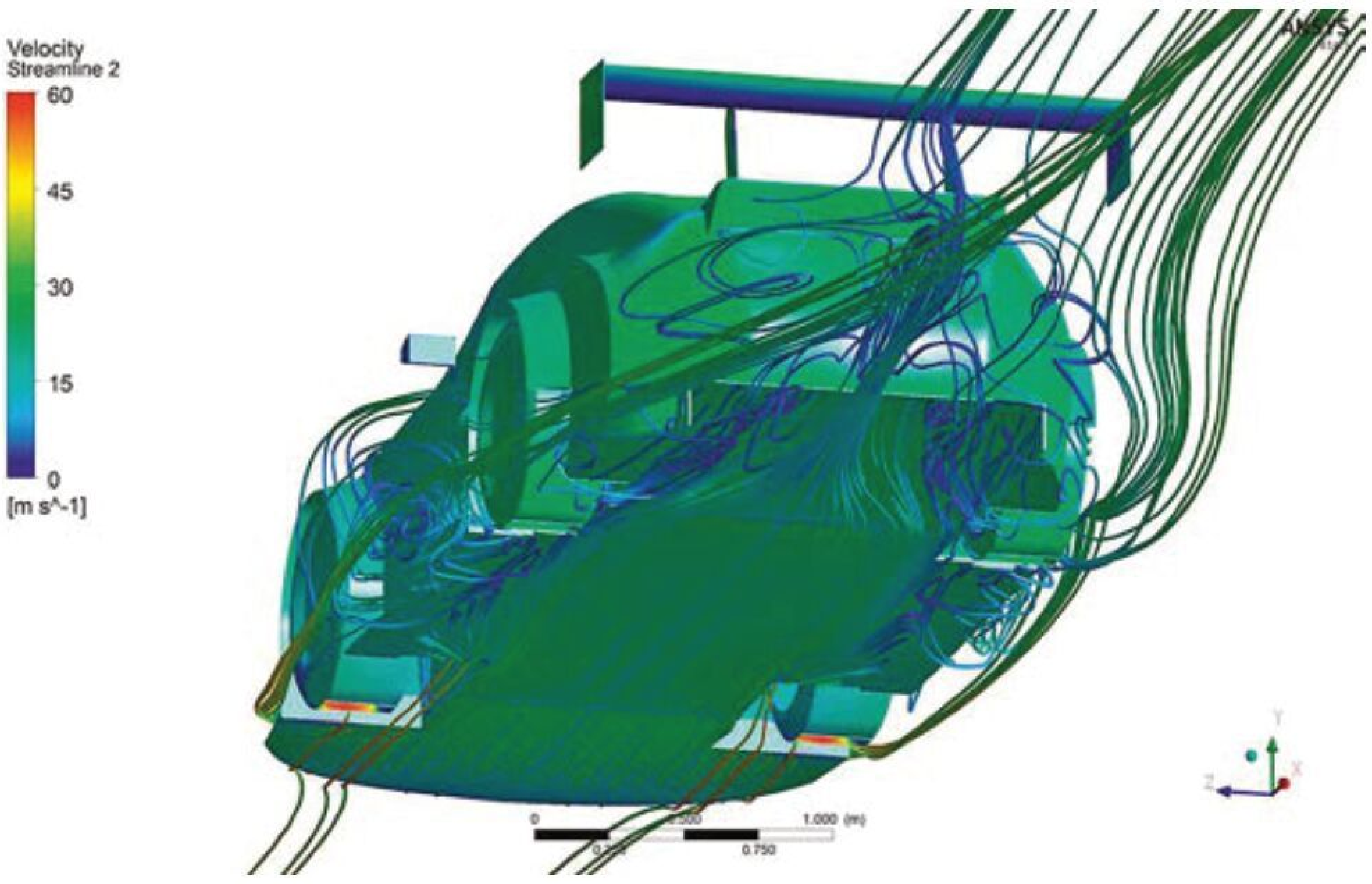


Figure 8: Reducing the roof angle of the diffuser to eight degrees eradicated the stall in the centre. The peak diffuser angle was lower than perhaps might have been expected

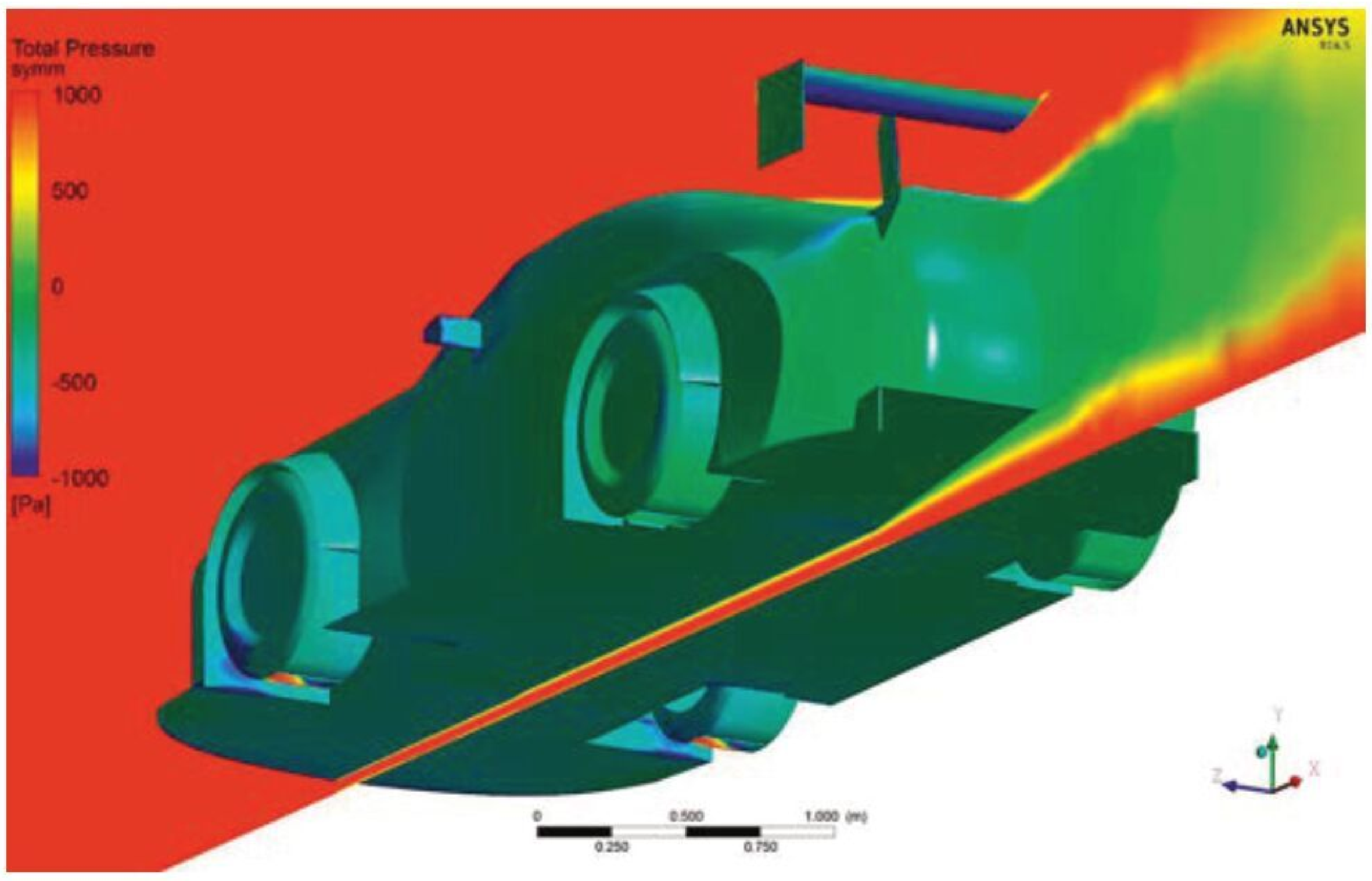


Figure 9: Comparing this with Figure 7, you can see there was less total pressure loss in the diffuser centre when its roof angle was reduced

The flow from the Ferrari F430 Scuderia GT3's diffuser centre was seen to be tidy...

...while the flow from the outer diffuser sections was untidy, reflecting what the CFD simulations indicated. This particular Ferrari was tested in the MIRA wind tunnel in 2010

Table 3: The effects of changing ground clearance

	CD	-CL	-CLfront	-CLrear	% front	-L/D
-10mm	0.46	0.94	0.37	0.56	40.0%	2.06
Baseline	0.45	0.91	0.36	0.55	39.1%	2.01
+10mm	0.47	0.82	0.30	0.52	36.9%	1.74
+20mm	0.48	0.81	0.28	0.53	34.5%	1.70

» In this instance, it would seem our assumptions about the effects of changing ground clearance were essentially borne out

downforce and efficiency (-L/D) at a diffuser angle of eight degrees.

Furthermore, as **Figures 8** and **9** show, there no longer appeared to be any signs of stall in the diffuser centre at eight degrees. So it would seem that on this particular model, at this rake angle and ground clearance, and in a configuration that featured a low wing angle at this stage, the peak diffuser angle was lower than might have been expected. There are other variables that could influence this, though, so the key lesson here is that it's unwise to make assumptions about any variable.

As an aside, if the streamlines in the outer sections of the diffuser in **Figures 6** and **8** appear disorganised, at least when compared to the tidy flow that converged in the centre of the diffuser, then compare them to the photographs above of the Ferrari F430 in the wind tunnel, which show typical flows emerging from the exit of the car's diffuser. A noticeable similarity, I think you'll agree.

Messy conditions

The CFD images give us a better indication of just why the flows emerging from this kind of diffuser look tidy in the centre but untidy outboard of that. The combination of the diffuser shape, the location of its transition and airflow coming off the inside of the rear tyres, to name but three of the numerous influential factors, create the messy conditions in the outer diffuser areas.

We rarely alter ground clearance (as distinct from rake) in wind tunnel trials, except perhaps for a quick check on one or two predetermined alternative heights, partly because it's assumed that running a car as low as possible is the right thing to do, so why squander wind tunnel time trying to prove that? The opportunity to examine alternative ride heights on the CFD model, however, was worth taking. The 'new' baseline model with eight-degree diffuser, 47mm splitter leading edge height, 60mm front ride height (FRH) and 75mm rear ride height (RRH) was lowered by 10mm and then raised by 10mm and then 20mm. The results are shown in **Table 3**.

In this instance, it would seem our assumptions about the effects of changing ground clearance were essentially borne out, with a general upward trend in drag and a downward trend in downforce with increasing ground clearance.

Ground clearance

Balance shifted rearwards as ground clearance was increased, primarily because splitter downforce declined. The responses were non-linear, with the biggest incremental changes between baseline height and +10mm on baseline, although it is unclear at this stage whether this response would be matched across the same ground clearance range in reality. **Figure 10** compares the surface pressures on the underside of the lowest and highest ground clearance

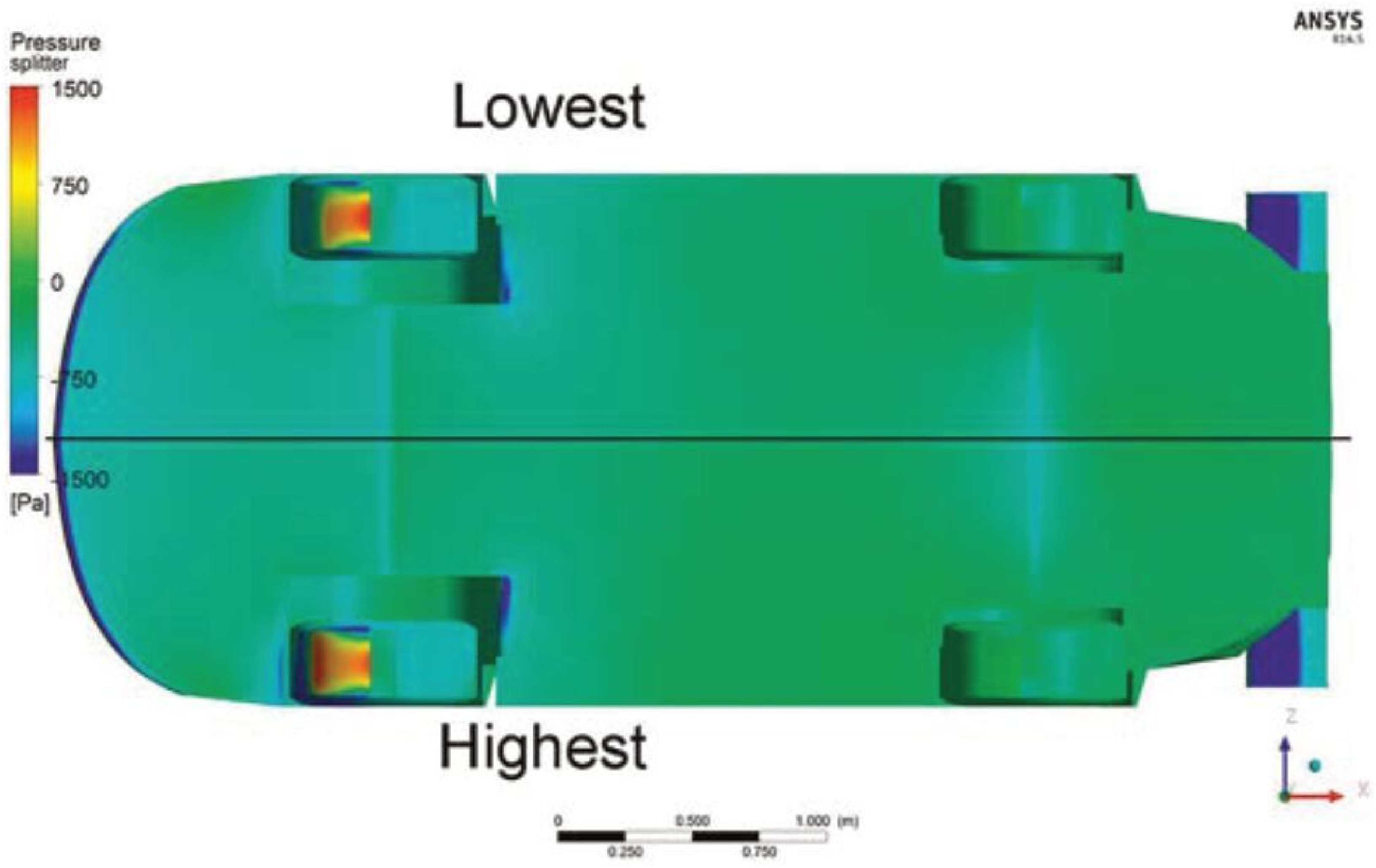


Figure 10: At the lowest ground clearance the pressure under the splitter was marginally lower, as shown by a subtle increase in the area of pale blue in the upper half of graphic

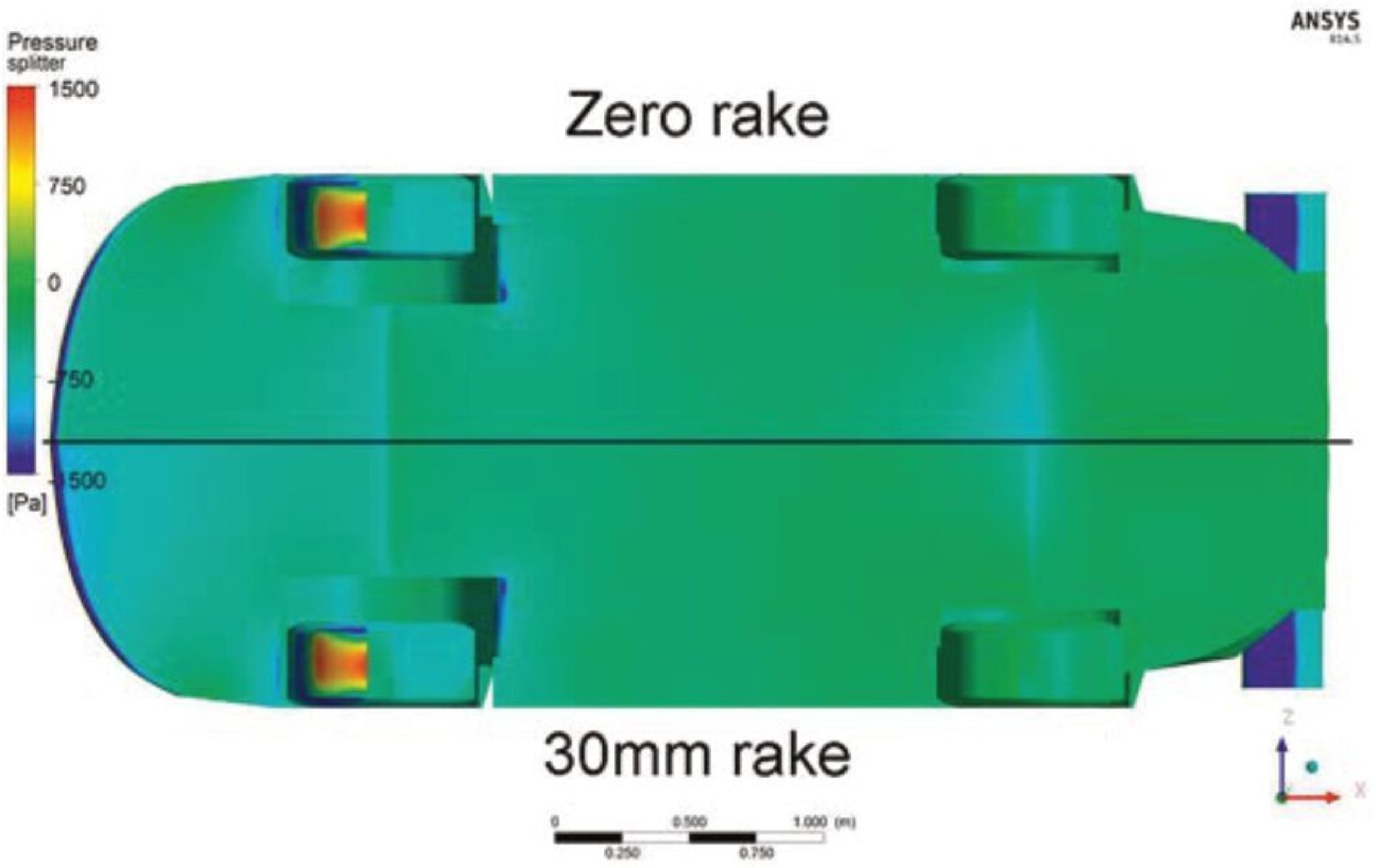


Figure 11: Rake change caused a forward shift in balance. The splitter panel exhibited greater pressure reductions at the highest rake angle compared to the zero rake case

Table 4: The effects of rake adjustments

	CD	-CL	-CLfront	-CLrear	% front	-L/D
Zero rake	0.44	0.88	0.30	0.58	34.0%	2.01
Baseline, 15mm rake	0.45	0.91	0.36	0.55	39.1%	2.01
30mm rake	0.46	0.92	0.43	0.49	46.4%	2.00

Table 5: The effects of pitch angle adjustments

	CD	-CL	-CLfront	-CLrear	% front	-L/D
Baseline, 0 pitch	0.45	0.91	0.36	0.55	39.1%	2.01
0.375deg pitch	0.48	1.05	0.52	0.54	49.0%	2.22
0.75deg pitch	0.51	1.27	0.76	0.51	60.1%	2.51

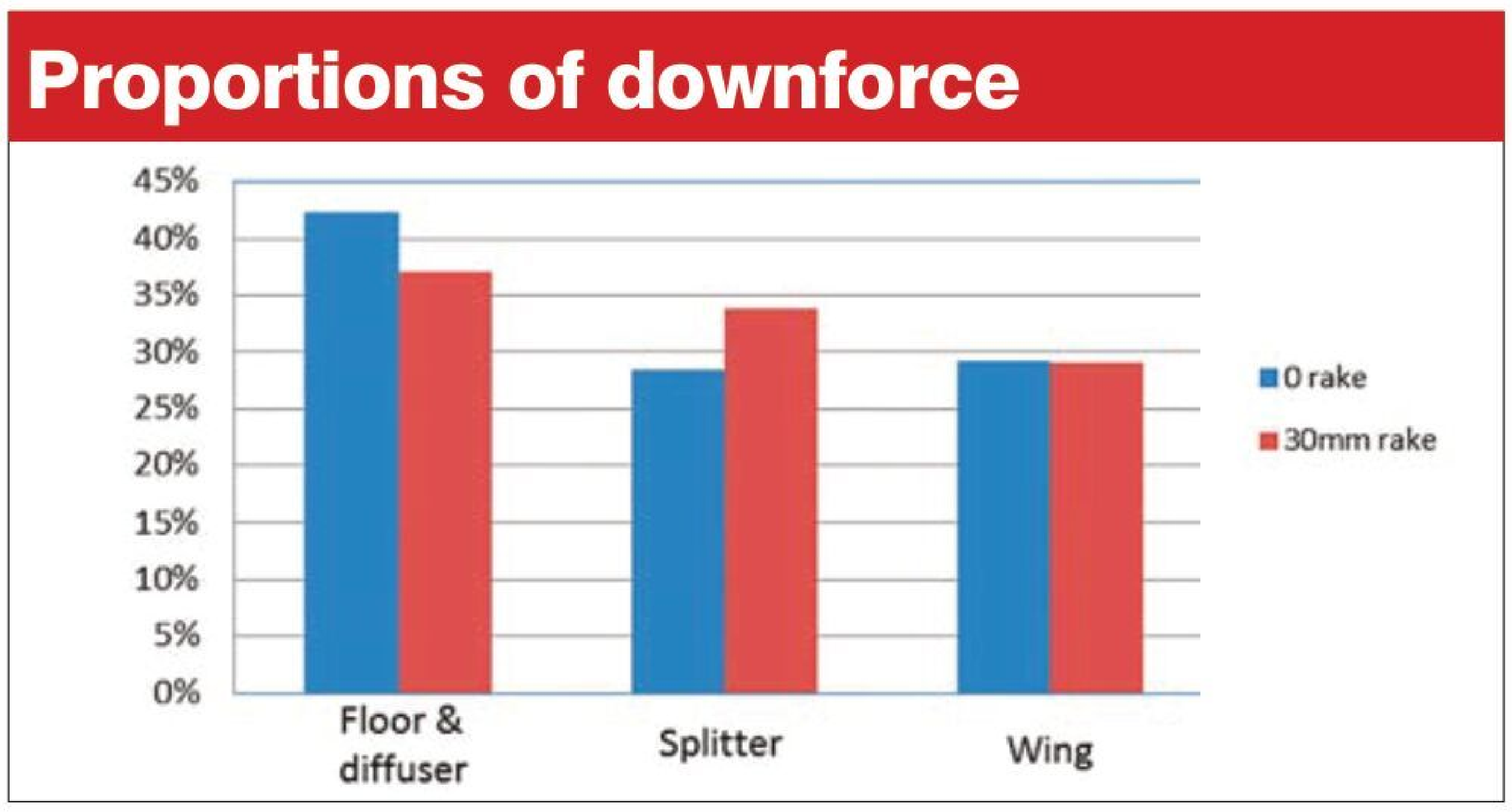


Figure 12: The contributions of the major component groups when rake was altered

models. The differences are subtle and concentrated mainly under the splitter panel, which extends back to in line with the front axle.

Rake angle

When rake is adjusted in our wind tunnel sessions, sometimes it's done with packers under the tyres, sometimes by adjusting the suspension. In the latter case it is possible, with preparation and care, to maintain a fixed splitter height and alter the car's rake angle by, effectively, pivoting the car about the splitter's leading edge. This is important if there is a minimum permitted splitter height in the series the subject car races in.

In CAD, it's very simple to rotate the car model (independently of the wheels), similarly to maintain a fixed splitter height and achieve different rake angles. This was the basis of the next set of runs, and the 'new baseline' model was rotated to zero rake (FRH and RRH both 52mm) and to 30mm rake (68mm FRH, 98mm RRH). In each case, the underside of the splitter leading edge remained at 47mm. The data are reported in **Table 4**.

There were some pretty clear responses in the coefficients to changing the rake angle. Drag and total downforce both increased by modest amounts as rake was increased. But front downforce increased by over 40 per cent over the rake range tested, while rear downforce decreased by 15.5 per cent. Balance moved more than 12 per cent forwards in absolute terms, while efficiency (-L/D) barely changed at all. So the predominant effect of increasing the car's rake was to move the balance forwards, and the modest total downforce increase was a secondary effect.

Figure 11 highlights where the surface pressure changes occurred on the underside. The splitter panel exhibited greater pressure reductions at the highest rake angle compared to the zero rake case, and the 'suction peak' at the diffuser transition was reduced at the maximum rake.

Figure 12 illustrates how the proportions of downforce generation changed from zero to 30mm rake. The floor and diffuser's proportion reduced while the splitter's increased. The rear wing's downforce increased by a very small amount, no doubt because of the small increase in its angle of attack, but its proportionate contribution remained unchanged.

Pitch angle

Whereas the results of the rake changes in the foregoing section could be regarded as indicative of steady-state conditions in different set-ups, pitch angle is a parameter that changes dynamically on a fairly continuous basis in most competition scenarios.

Our simulations are by definition steady state but, by applying different pitch angles to the model and comparing them with the baseline data, we can get some idea of the changes in aerodynamic performance across a dynamic pitch angle range. So in this instance, the baseline model was rotated about an imaginary pitch centre halfway along the wheelbase and at wheel axle height, and two angles were successively applied. 0.375 degrees changed the splitter leading edge height, front ride height and rear ride height from 47mm / 60mm / 75mm to 31mm / 52mm / 83mm, while 0.75 degrees changed them to 15mm / 45mm / 91mm. The data are shown in **Table 5**.

The responses in this instance were even stronger than when rake angle was adjusted. The dominant factor here was the increase in front downforce, which more than doubled from the baseline to the 0.75 degrees pitch angle, with a commensurate shift in aerodynamic balance.

Figure 13 shows the surface pressures on the model's underside. The big increase in suction under

> **» The predominant effect of increasing the car's rake was to move the balance forwards, and the modest total downforce increase was a secondary effect**

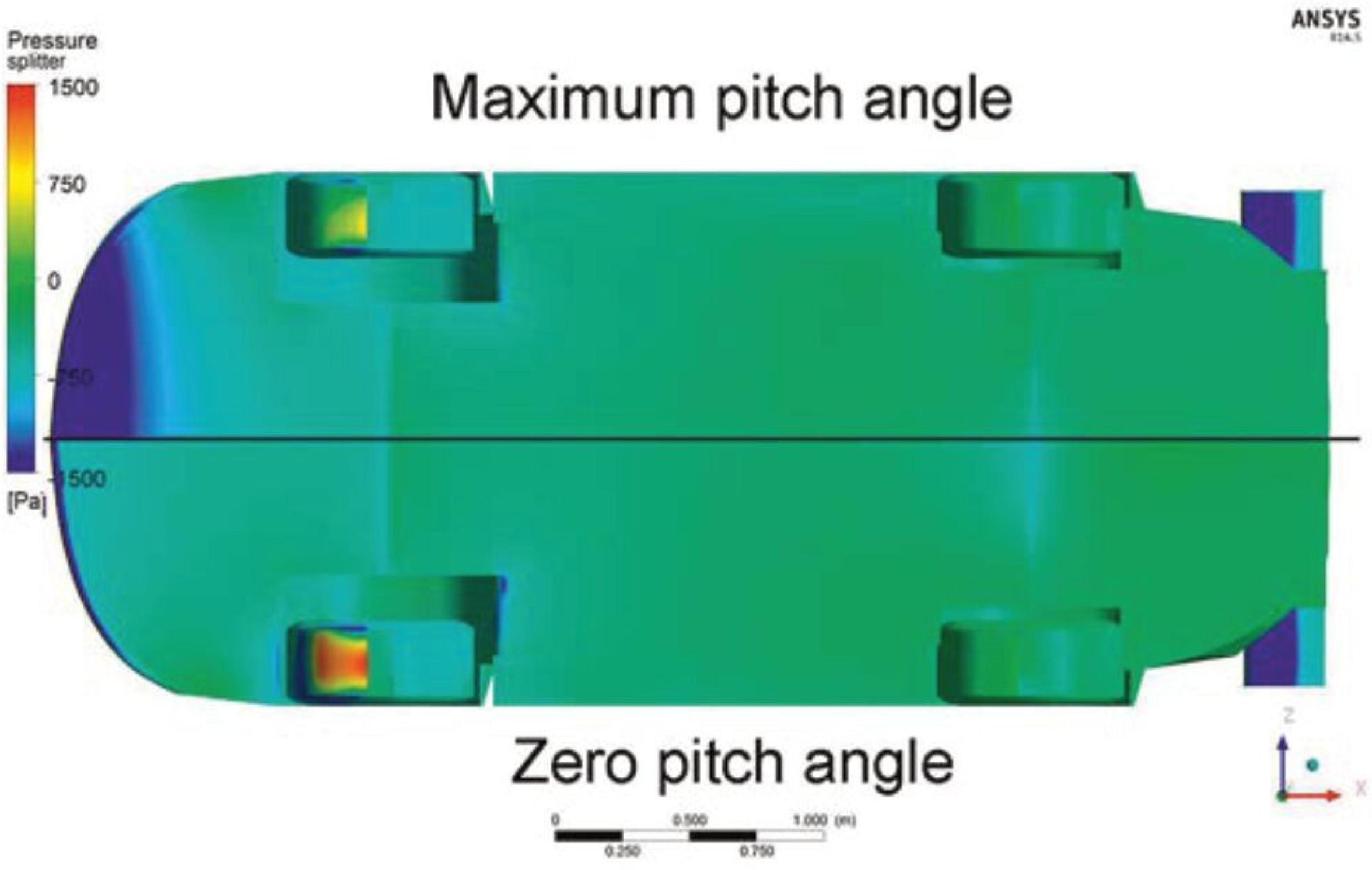


Figure 13: Pitch changes caused big shifts in pressure distributions on the underside

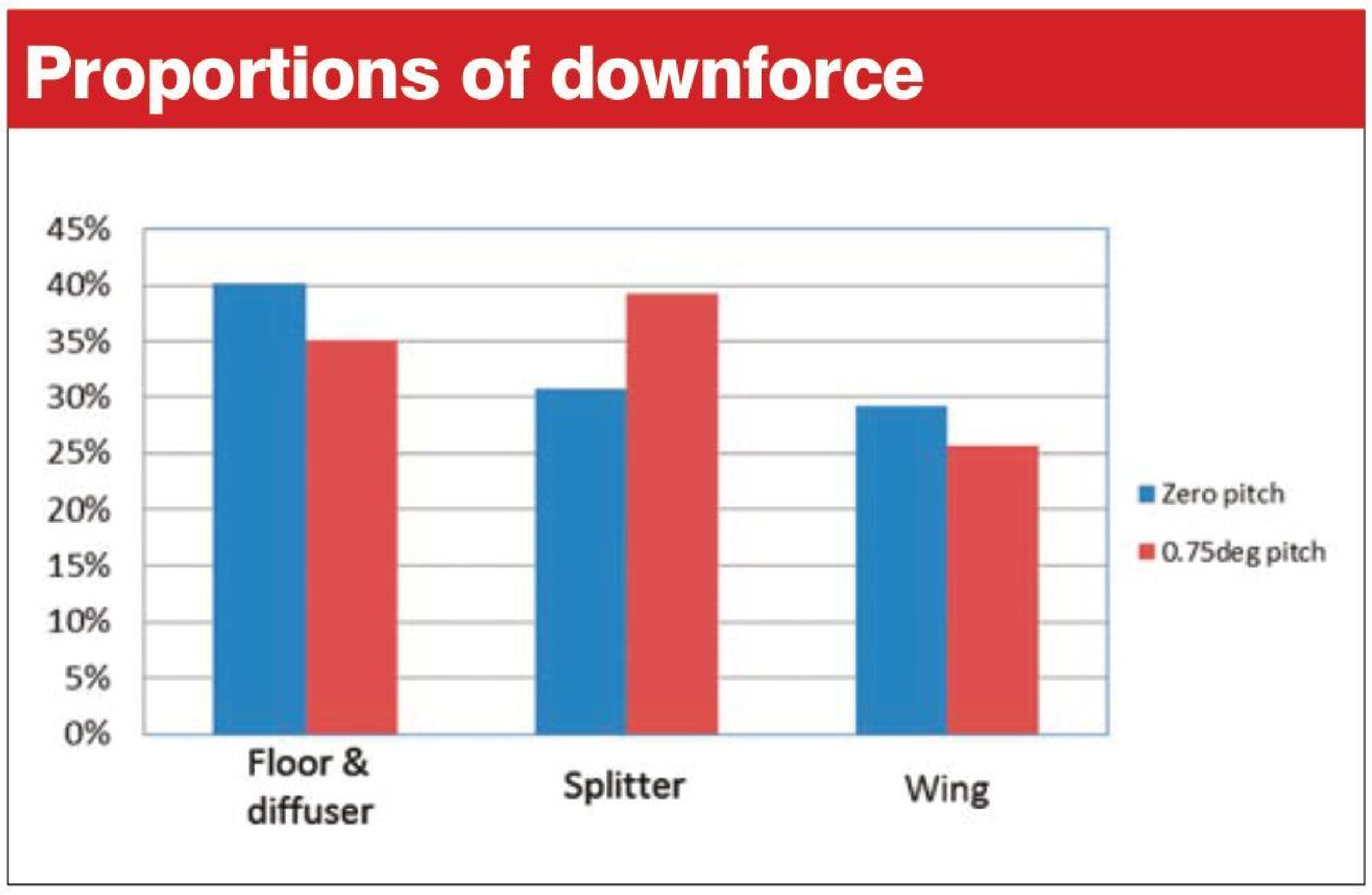


Figure 14. Pitch changes also caused some big shifts in the downforce contributions

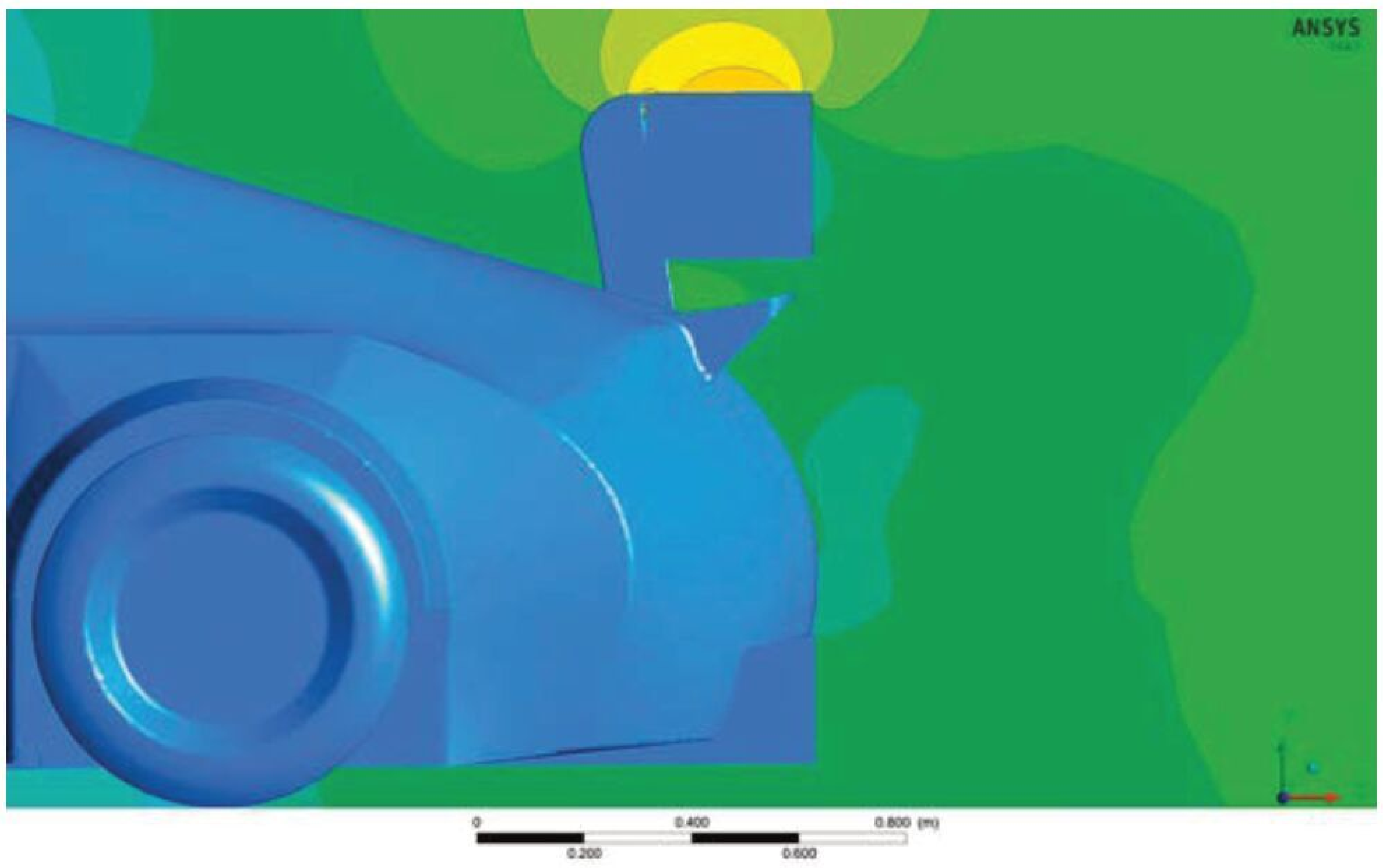


Figure 15: Diffuser overhang was also examined. Terminating the diffuser at the rear extent of the body ensured the lowest wake pressure was exerted on the diffuser exit

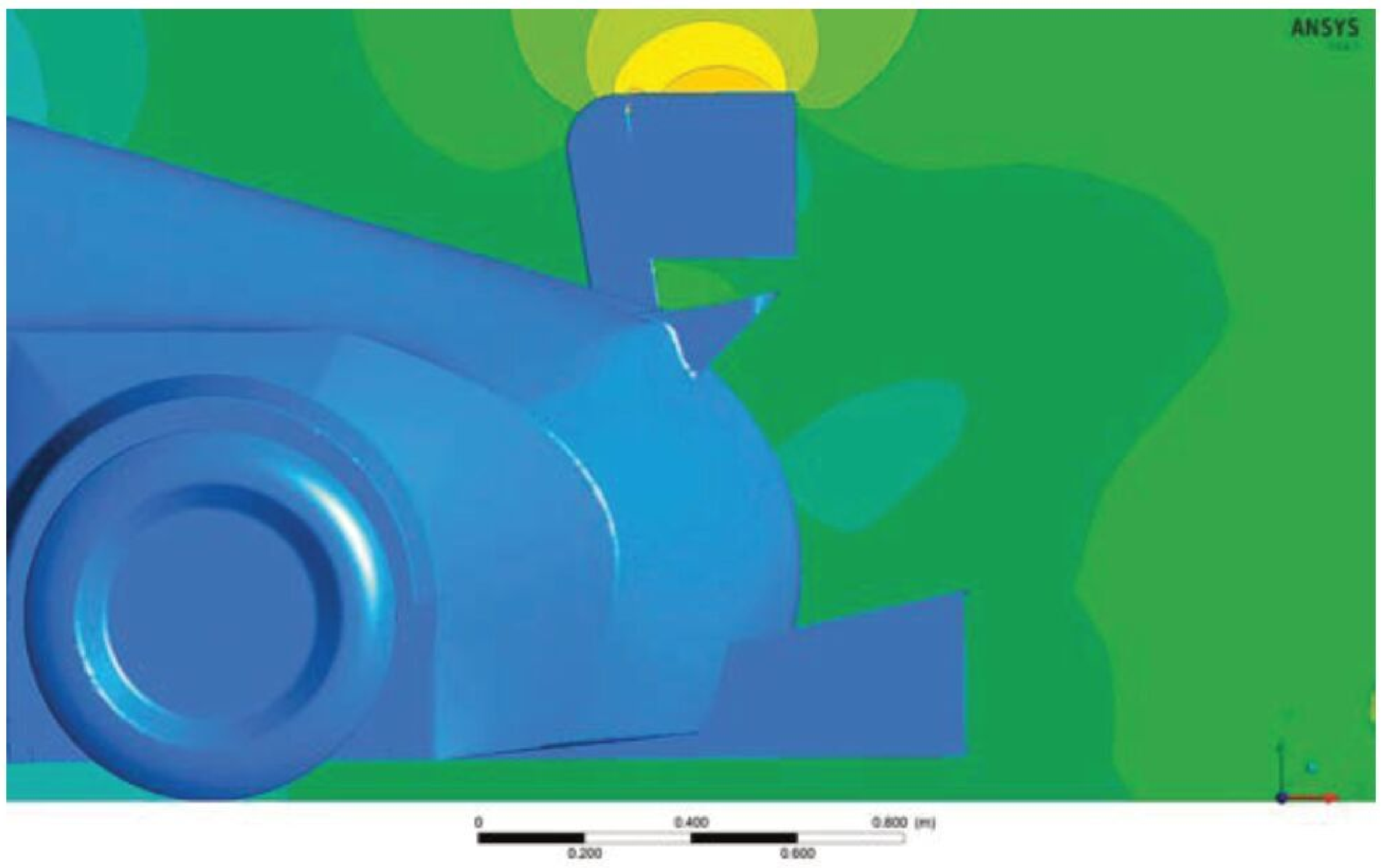


Figure 16: Extending the car's diffuser saw slightly higher pressures at the diffuser exit

the splitter is very obvious when compared with the zero pitch case. Note also other differences such as the change in pressures on the 'exposed' lower portions of the front tyres, and the reduced suction at the diffuser transition, both presumably the result of reduced mass flow under the car when the splitter was so much closer to the ground.

Figure 14 shows downforce contribution changes. This kind of pitch change would occur under heavy braking, so the aerodynamic balance shift would reinforce the mechanical weight transfer during the braking phase. Whether or not this was deemed detrimental or beneficial would be a matter of driver and race engineer preference. Certainly, the different aerodynamic loads at the alternate ends of this pitch angle range would see a significant difference in the vertical forces acting on the front tyres.

Diffuser overhang

A question frequently asked during wind tunnel sessions is how far should a diffuser protrude at the rear when there are no rule restrictions? In unrestricted categories, like Time Attack for example, diffusers that protrude well beyond the rearmost extent of the original bodywork are frequently seen, and this seems to prompt others to ask the question, or else follow suit on the assumption that it's the correct thing to do.

Having had no opportunity to evaluate in the wind tunnel, gut feel suggested there would be trade offs that would not guarantee additional downforce from a longer diffuser.

> **» Gut feel suggested there would be trade offs that would not guarantee additional downforce from a longer diffuser**

Table 6: The effects of extending the diffuser

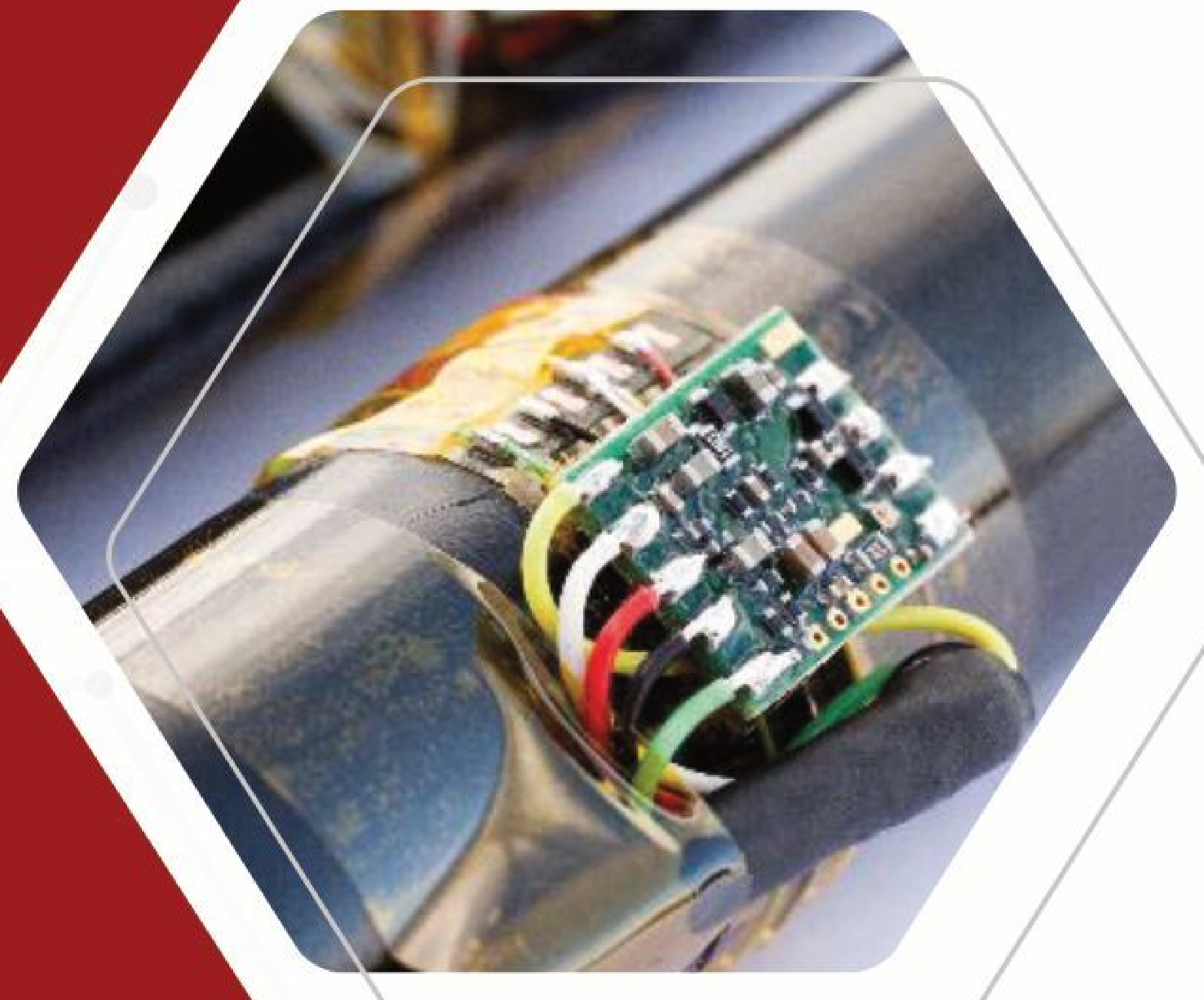
	CD	-CL	-CLfront	-CLrear	% front	-L/D
Baseline diffuser	0.46	0.85	0.33	0.52	38.8%	1.87
+100mm diffuser	0.46	0.84	0.33	0.51	38.9%	1.84
+200mm diffuser	0.46	0.84	0.34	0.49	41.0%	1.80
+300mm diffuser	0.46	0.86	0.34	0.52	39.2%	1.87

On the one hand the diffuser volume would be greater but, on the other hand, would not the geometry of the underbody forward of the diffuser need to be configured to enable a bigger diffuser to be filled so as to provide a beneficial contribution?

Furthermore, extending the diffuser rearwards may push its termination into areas of not such low pressure in the wake, when it is preferable to exploit the lowest wake pressures immediately aft of the car to help draw air through the diffuser. Extending the diffuser into the wake also subjects the top surface of the diffuser roof to the wake's low pressure, which would create an increment of positive lift that, at the very least, would negate any above / below pressure differential in the diffuser extension. And unless the rear wing is moved aft too, which may result in an undesirable balance shift, any positive interaction between the wing and diffuser would be weakened by the greater distance between the wing and diffuser exit.

Clearly, these aspects could be optimised as part of an initial design, but the original question remains valid. To find out, three longer diffusers were evaluated on our initial baseline model, and the results are shown in **Table 6**.

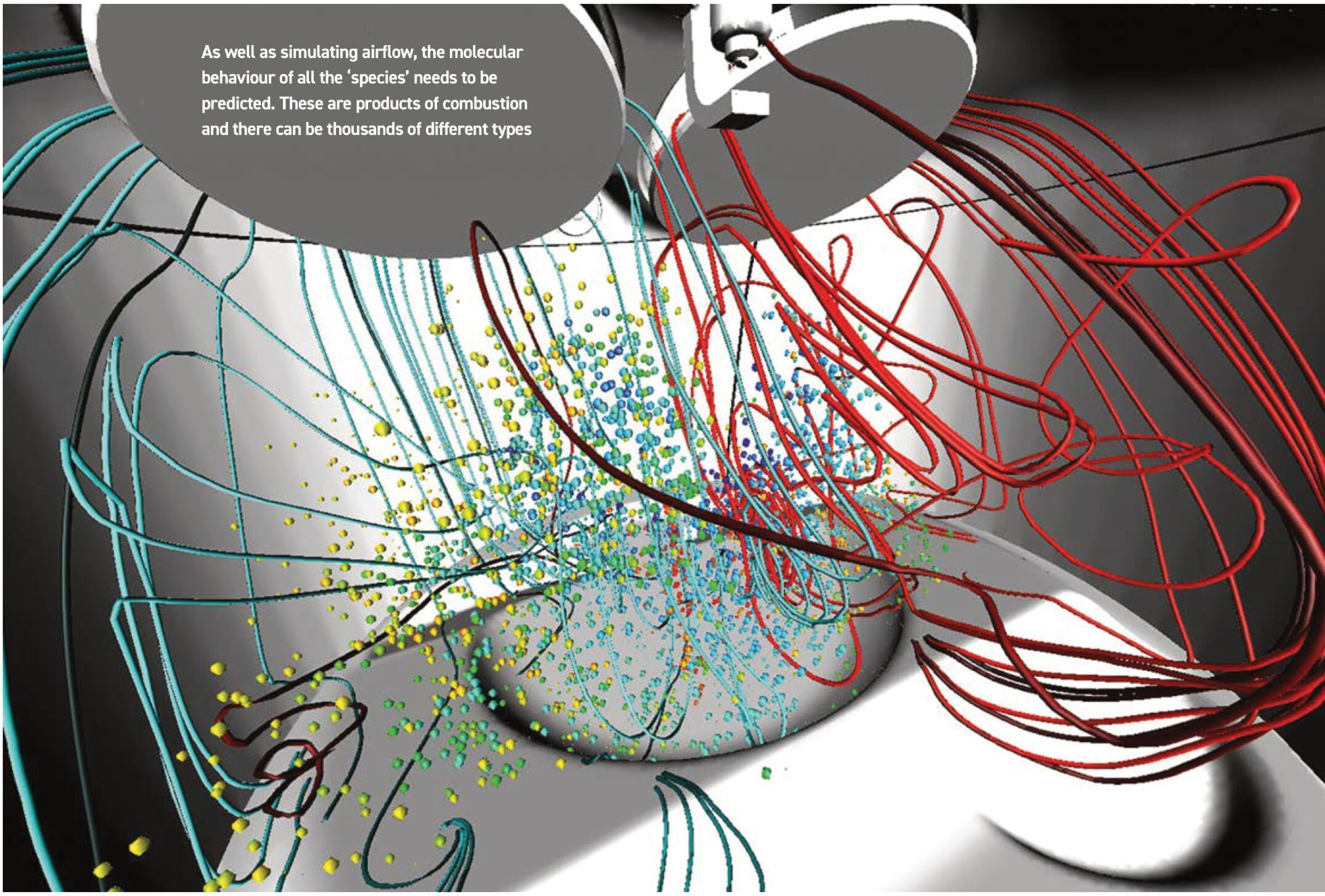
The short answer, then, is that increasing the diffuser overhang had negligible influence on any of the key parameters, and there was no tangible change to the downforce generated by the floor and diffuser as its length was extended (see **Figures 15** and **16**). However, the caveat should be added here that this trial was done on the original 12-degree diffuser, so further work should be done on a better optimised diffuser to verify these findings.



Meshy business

There are few tasks as complex as replicating the workings of a power unit in the virtual domain. *Racecar* uncovers the secrets of the rapidly developing engine modelling technology

By GEMMA HATTON



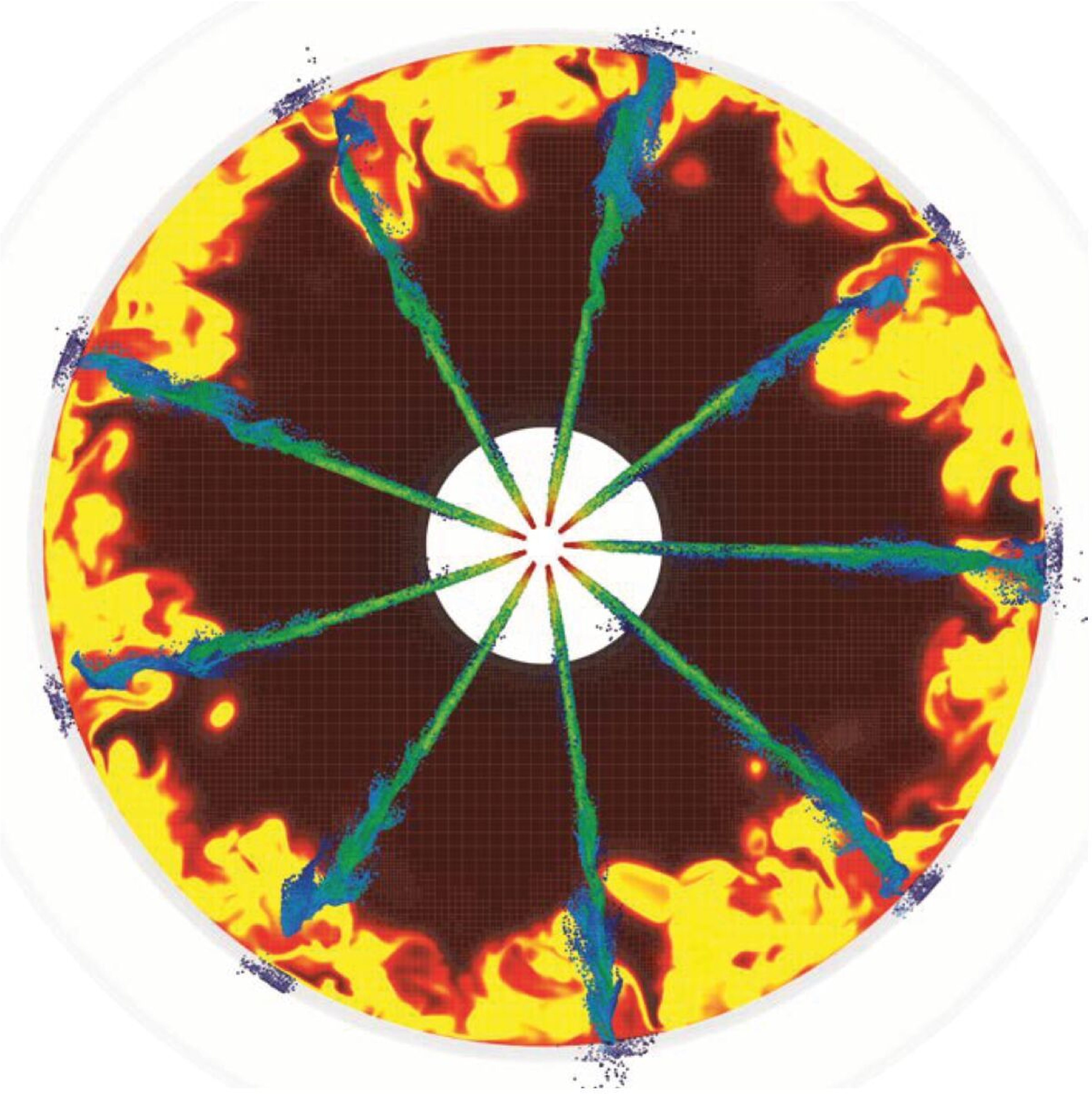
As well as simulating airflow, the molecular behaviour of all the 'species' needs to be predicted. These are products of combustion and there can be thousands of different types

Understanding the science behind modern racecar engine design is one thing, entering the virtual environment to discover how certain companies are now characterising the phenomena of combustion with equations to simulate and optimise engine performance is quite another, but we spoke with leading lights in the field to find out more about this exciting new area of technological development.

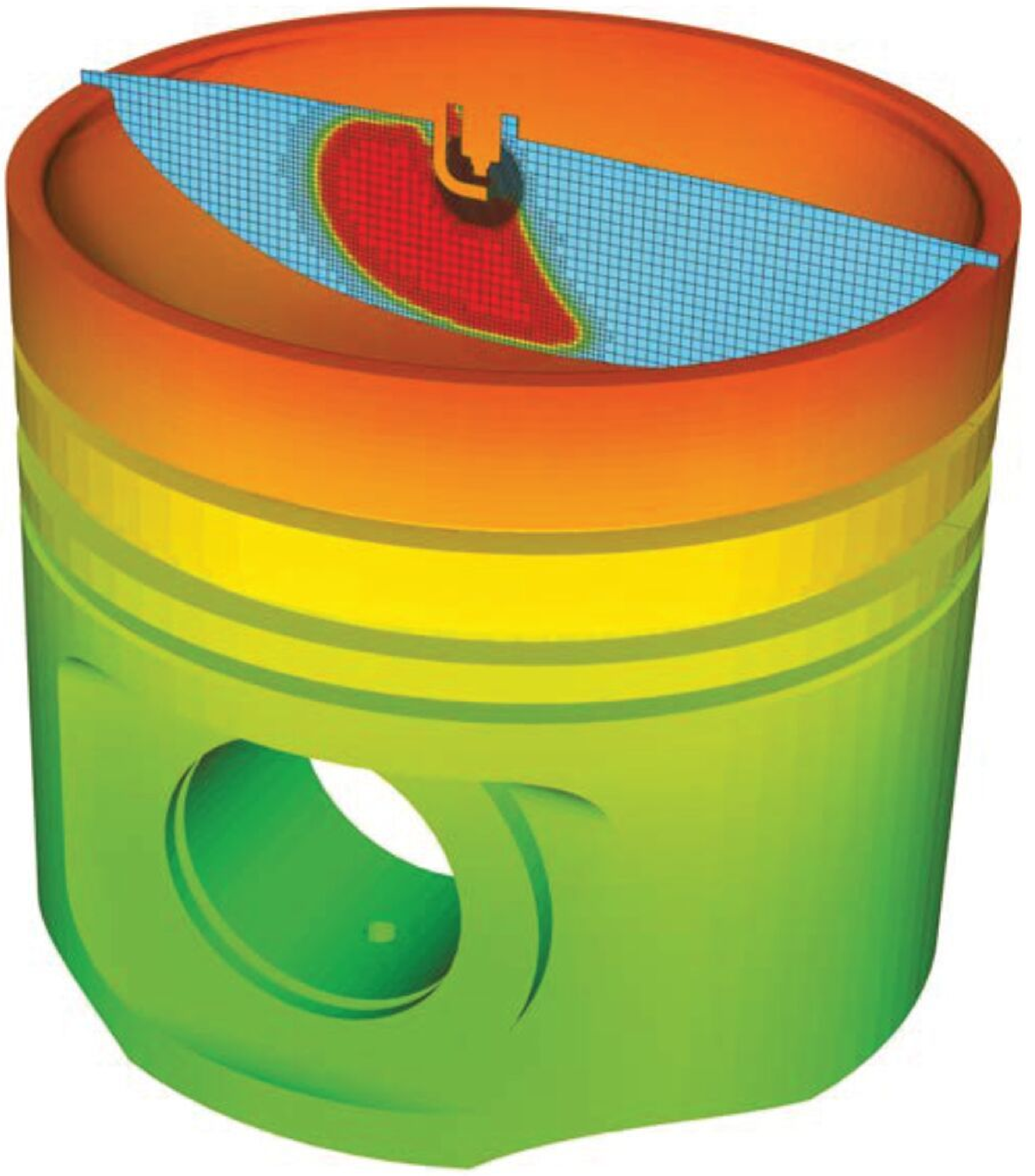
Today's Formula 1 engines generate approximately 950bhp, with some rumoured to exceed 1000bhp. To generate that amount of power, the engine needs to complete 200 ignitions in the time it takes you to blink. This equates to a total of 46,000 combustion events within a single lap of an F1 circuit. To replicate that in the virtual world is a monumental challenge – so where do you start?

We know swirl and tumble are crucial in maximising the amount of air burned with each droplet of fuel as modern regulations continue to encourage lean burn. Both techniques are initiated through clever design of the intake ports, and this is therefore one of the first of the models that needs to be implemented.

'In-cylinder flow simulation includes at minimum one, often multiple, engine cycles,' says Maik Suffa, Solutions Manager Virtual ICE Development, Combustion and Emissions at AVL. 'The macroscopic structure of the flow within the cylinder is initially defined by the mass and velocity of the incoming air, as well as the port and piston designs, the valves, valve seats and valve timings. The standard turbulence model deployed with AVL Fire is the k-ζ-f model. In contrast to the widely-used k-ε or k-ω models, the three-equation k-ζ-f model combines the stability of two equation models with improved



This shows a CONVERGE Large Eddy Simulation (LES) of fuel injection, ignition and combustion in a heavy-duty diesel engine. As developments in computing power continue to increase, we could see a shift to LES simulation in the next 10 years



Adaptive Mesh Refinement (AMR) in CONVERGE. Here it's been used to resolve the turbulent flame front in this single cylinder petrol DI engine simulation. The gas-phase flow and combustion has been coupled to the solid piston heat transfer calculation

accuracy for both flow and heat transfer. This is visible especially when simulating swirling or tumbling flows in combustion engines. Furthermore, the model doesn't require finer grids compared to the two equation models, it can be used on relatively coarse grids without losing robustness while still improving accuracy.'

Next to be modelled is the fuel injection, and this system is designed to achieve an evenly defined distribution of fuel within the turbulent in-cylinder airflow. 'Simulating fuel injection requires the handling of multi-phase flow phenomena,' Suffa says. 'Conservation equations for both the gas and the liquid phase need to be solved simultaneously. With respect to the liquid phase, the fuel spray simulation is based on the Discrete Droplet Model method. The droplets are tracked in a Lagrangian way through the computational grid, which is used to solve the gas phase equations. Both the gas and liquid phase are fully coupled.'

Fuel break-up

But it's not just about tracking the movement of the fuel droplets. Their behaviour and interaction also needs to be simulated. This includes any primary and secondary break-up, turbulence dispersion, distortion, drag, collision and coalescence as well as the interaction with system boundaries that can lead to wall film formation.

'The intensity and frequency of the primary fuel break-up is related to the turbulent velocity fluctuations induced by the flow in the injection nozzle. Therefore, our Fire software allows the output of the injection nozzle simulation to be utilised as input to the fuel primary break-up modelling,' says Suffa. 'This link is made via a so-called nozzle-file, which contains a record of the time dependent velocity, turbulence, density and temperature of both the liquid and gaseous fuel phases exiting the individual nozzle orifices. During the subsequent in-cylinder spray simulation, the data written into the nozzle file is used to initialise the start locations and properties of the droplets and hence the primary break-up.'

Spark life

As the piston reaches TDC, the fuel and air mixture is ignited. To guarantee fast and complete combustion, a moderate flow velocity, high turbulence kinetic energy and a stoichiometric mixture around the spark plug must be achieved. Advanced ignition models, such as the recently developed CADIM (Curvature And Diffusion Ignition Model) will allow detailed modelling of the spark and the energy transfer between spark and mixture. This is another pre-condition for an accurate combustion solution.

'The combustion process can be effectively simulated by CFD software,' Suffa says. 'Generally, there are two types of combustion models. The first category is called intrinsic combustion models, which includes models such as the ECFM [Extended Coherent Flamelet Model] family or the recently more popular flame tracking models. These models will solve a relatively small number of reactions involving only a few species. They are fast and run in parallel with the CFD solver.'

In combustion modelling for spark-ignition engines, the biggest challenge is the exact computation of the flame propagation whilst predicting the consequent molecular behaviour of all the species involved in the burning process. In SI engines this is often overcome by using explicit flame tracking models, such as the FTPM (Flame Tracking and Particle Method). This method is popular because it can precisely calculate the time-dependent flame position and so predict heat release as well as emissions. This is achieved by deploying sets of Lagrangian particles. Reaction mechanisms are then applied in regions before and after the flame, which allows the computation of pre-ignition, heat release and emissions.

These 'species' are defined as the products of combustion and alongside the three main chemical compounds of CO_2 (carbon dioxide), O_2 (oxygen) and N_2 (nitrogen) there are also

> **» 'Defining the mesh is a constant balance between having a fine resolution for increased accuracy, while maintaining a coarse resolution to reduce computational time'**

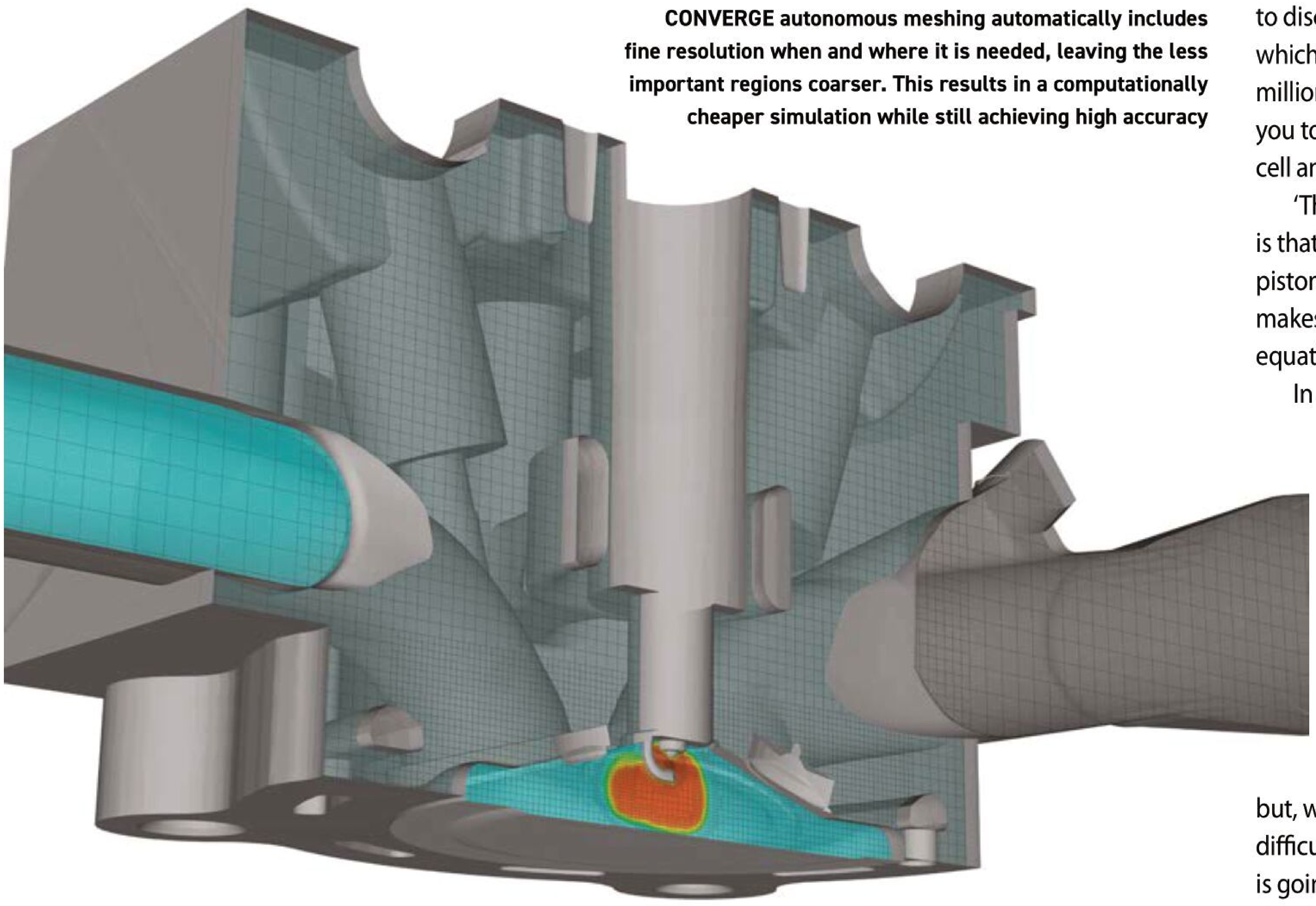
> **» 'Solving large reaction mechanisms comes with a time penalty'**

thousands of different variants of species, all of which need to be accurately modelled.

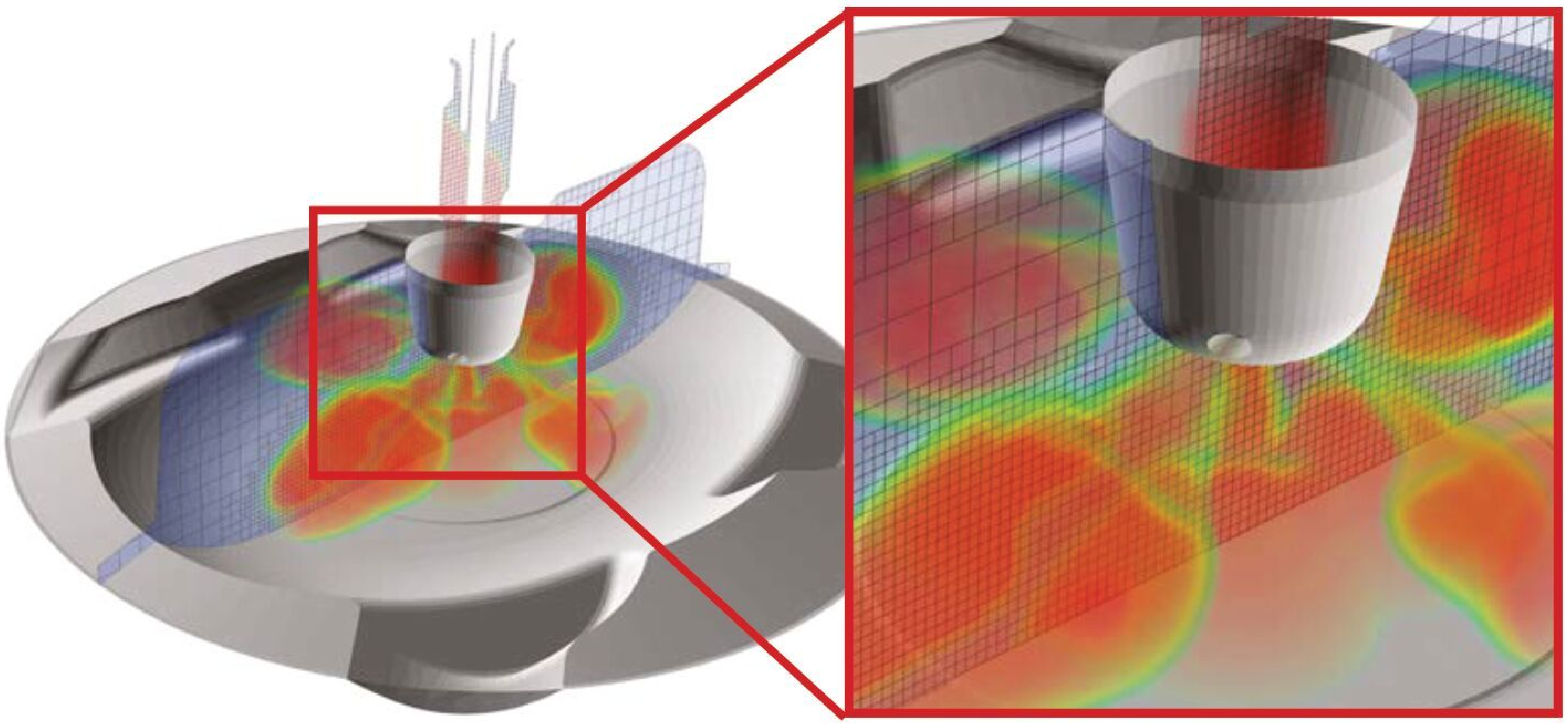
'The second category of combustion modelling is referred to as detailed chemistry or reduced chemistry, which is rather confusing terminology,' admits Suffa. 'We call it detailed because we are solving mechanisms of higher complexity compared to when using in-build models. For example, instead of simulating 10 to 20 species, detailed reaction chemistry often deals with 200, even 2000 species. However, even the most complex mechanisms still can't directly reflect the chemistry of the real fuels, which is why some people still refer to this category as reduced chemistry.'

Of course, solving large reaction mechanisms comes with a time penalty, which is directly dependent on the number of involved species and reactions. Furthermore, the reaction mechanism must fit exactly to the specific fuel that is being simulated. A suitable reaction mechanism reflects the different characteristics of gasoline, diesel or other fuels as well as the varying qualities of these fuels.

'The prediction of global values, such as pressure or temperature traces is relatively simple, even with intrinsic combustion models,' Suffa says. 'By solving detailed reaction mechanisms it is possible to compute the chemistry of a specific air / fuel mixture with all its local variations much more accurately. Therefore, in spark-ignited engines a good combustion solution requires sophisticated models to track the flame, to compute reaction chemistry in pre- and post-flame zones and account for the interaction of chemistry and turbulence. Also, what many people forget is a combustion simulation can only be as good as the models used to simulate flow, turbulence and heat transfer, fuel injection, fuel wall interaction and ignition. All these models are essential and must perform well. Only then can you start thinking about modelling combustion, otherwise your simulation will be just wasted development time and money.'



CONVERGE autonomous meshing automatically includes fine resolution when and where it is needed, leaving the less important regions coarser. This results in a computationally cheaper simulation while still achieving high accuracy



The automatic and adaptive meshing capability allows engine designers to explore configurations that were previously far too difficult to mesh. Note the differences in mesh resolution depending on the area of interest

Navier Stokes

Now we have a rough run down of how combustion events can be characterised by theoretical equations, the question is how to compute them in CFD software.

'The Navier Stokes equations are the governing equations for fluid flow, and we use numerical methods in CFD to represent the partial derivatives of these equations and ultimately solve them,' explains Kelly Senecal, co-owner and VP of Convergent Science. 'However, similar to any CFD problem, you have to discretise the overall geometry or domain, which means you have to divide it up into millions of cells, creating a mesh. This then allows you to solve the Navier Stokes equations at each cell and at every time step.

'The challenge with in-cylinder simulations is that the geometries of the ports, valves and pistons tend to be extremely complex, which makes defining the mesh and solving the equations much more difficult.'

In any CFD simulation, defining the mesh is a constant balance between having a fine resolution for increased accuracy, while maintaining a coarse resolution to reduce computational time. To get around this issue, often the resolution is only increased in areas of interest, such as the area under the spark plug, while larger cells are used in areas of less interest. Where and when to increase the resolution is mostly user defined but, with engine modelling in particular, it is difficult to know what the combustion process is going to look like (which is, of course, why the simulation is being done in the first place) and therefore where to refine the mesh.

Refining the mesh

'You would have to use a fine resolution across the whole domain just to make sure you catch all the areas of interest, and that can get expensive because that's a lot of cells to solve for,' notes Senecal. 'We have developed an Adaptive Mesh Refinement (AMR) technique that solves this problem because the user no longer has to guess where to refine the mesh. The solver does it automatically using all the local information of the flow as it is solving it.

'AMR looks at the curvature or second derivative of the variable it is trying to solve, whether that be velocity or temperature and so on. If there is a high curvature in the

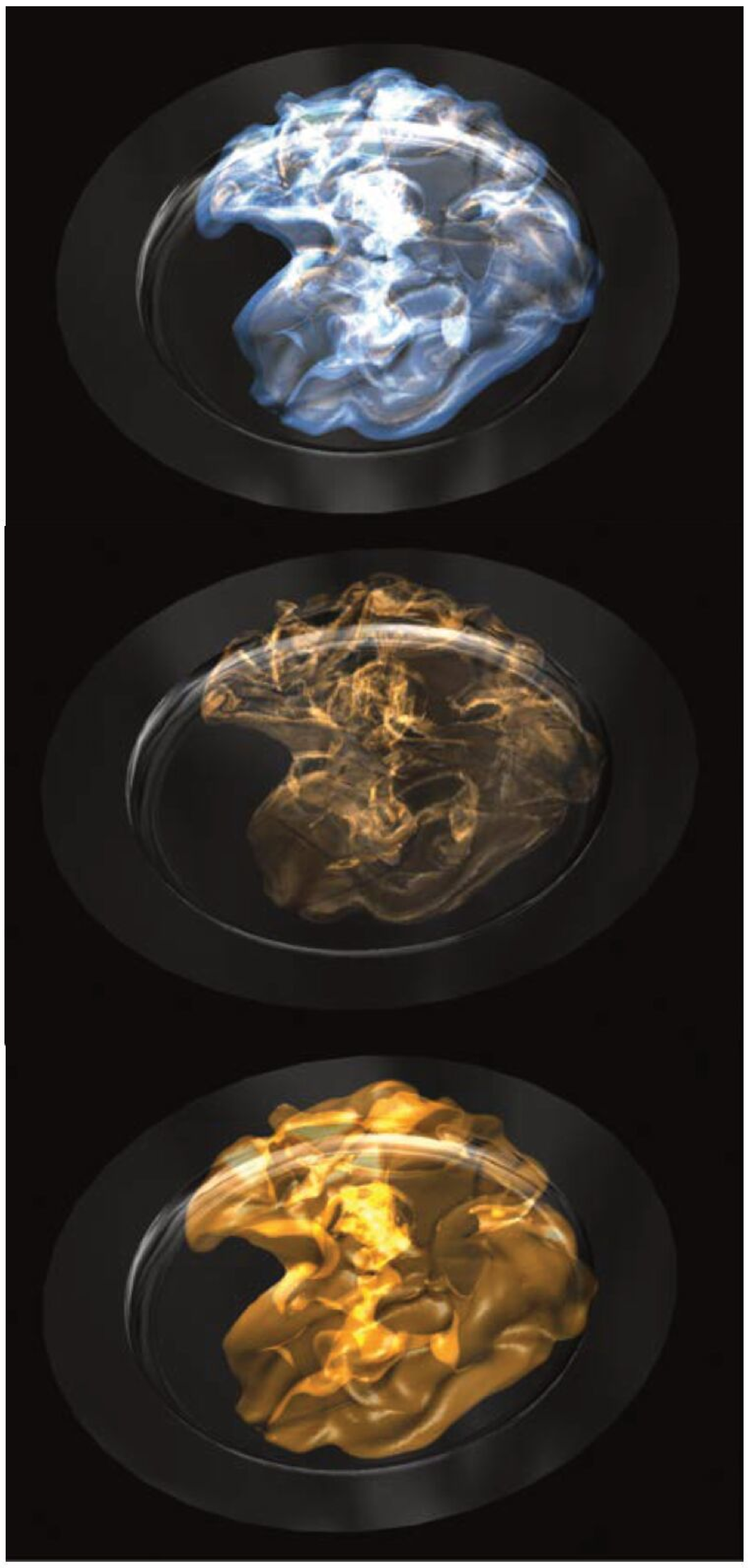

LifeCheck
STAY
ON TRACK
AND DRIVE UP
PERFORMANCE
MOTORSPORT INDUSTRY ASSOCIATION
MEMBER

velocity or temperature field then the code will automatically add more resolution in that area to resolve the flow feature pattern. It does this at every time step, so it is adding or removing cells dynamically, as and when it needs to, to best solve whatever the flow situation is at that particular time step.'

Three-directional code

Ideally, to achieve a fine mesh in areas such as the valve seat, the code has to refine in all three directions. This essentially means the original cube-shaped cells are chopped in half along all three axes. The benefit of this method is the flow is not influenced because you are simply resolving in all three directions. However, in doing this you are adding more cells, which increases both time taken and cost.

» The beauty of this type of automatic meshing is that it is coupled together with the solver



Predicting the flame propagation is the biggest challenge in engine modelling, particularly as hundreds of thousands of species are generated and each one has its own molecular behaviour

'This is where boundary layer meshing comes in, because this refines the mesh normal to the boundary and so the shape and aspect ratio of the cells is very different,' Senecal adds. 'Therefore, the code is resolving at high resolution close to the boundary, but a coarse resolution away from the boundary.

'The results from this method are just as good as resolving in all three directions, but the efficiency is greatly improved. This type of boundary layer gridding, coupled with our patented autonomous meshing algorithms, is another revolution in meshing, and is a big part of our next version of CONVERGE software.'

The beauty of this type of automatic meshing is that it is coupled together with the solver so, rather than having to wait for the mesh to be generated before running the simulation, the code defines the mesh and solves it simultaneously. All the users need to do is supply the CAD geometry of their cylinder, define the base mesh size and turn on AMR for the variables of interest.

'Generating the mesh has traditionally been one of the bottlenecks when it comes to simulating engine CFD, because it can take a very long time, and even once it's done there can be issues with skewed cells or anomalies,' explains Senecal. 'By taking all of that away from the user and putting that into the CFD code, the user can now spend more time analysing the results and doing real engineering.'

The wider picture

Zooming out from in-cylinder simulation, there are many other areas of an engine that need to be modelled, such as the airflow through the intake and exhaust manifolds, the interaction between the mechanical components, as well as the lubrication and cooling strategies. Accurately modelling how all these systems interact is essential to obtaining reliable power and heat release outputs.

The propulsion system physical models can then be integrated into the vehicle model by means of physical connections describing action-reaction relationships. This allows driveability, performance and diagnostics to be optimised as well as proof of new concepts such as the 2014 F1 hybrid powertrains and the hybridisation of ancillaries in endurance racing.

'We create the vehicle models by first building up the individual assemblies such as the air intake, the exhaust system, the combustion models and the mechanics,' explains Mike Dempsey, who is managing director at Claytex. 'Once we've tested and calibrated each system, and the engine as a whole, and are happy with the results, we integrate it into the overall vehicle model.

'Often the biggest challenge is integrating the control system, which could have been created in many different ways and might not even exist as an executable model, only as the real physical controller,' Dempsey adds. 'Once you start simulating the whole vehicle context, you need to have the controller as part of that model to operate the engine correctly and it needs to be provided with the right inputs.'

A further challenge of building up and simulating a vehicle model is managing the different time step requirements of each sub system to capture accurate data without increasing computational performance.

'Most simulation occurs in the purely virtual environment and uses a variable step solver that adjusts the time step depending on how quickly things are happening within the simulation,' explains Dempsey. 'However, when you are running in real time and you are integrating HIL [Hardware in the Loop] rather than just simulating in the virtual environment, you can end up running different parts of the model at different time step rates. A combustion model, for example, will run at 0.1-0.2ms time step, because any larger time step will lose the detail. Driving simulators, on the other hand, typically run at 1ms, so managing the different time steps within the same system can be very challenging.'

Hundreds of thousands of equations are required to run these engine models and each of these complex equation structures can only be solved by iteration at every time step, which can take an extremely long time. Therefore, these equations need to be re-formulated so the individual system becomes smaller, or the need for iteration is removed, making it much easier for the solver to deal with once the model is compiled. That in turn improves efficiency.

'Dymola, which is the simulation environment we use, performs automated symbolic manipulation,' Dempsey says. 'This takes those complicated systems of equations and manipulates the algebra to end up with the most efficient set of equations possible, and therefore runs with a smaller number of equations. The trick is to reduce the number of equations without eliminating any of the details in the model, and this is where Dymola uses a range of complicated maths techniques to achieve this. So rather than relying on the simulation engineer having extremely good maths skills, it relies on the maths skills of Dymola, which has been programmed by specialists in symbolic manipulation.'

Scalar model

Let's take the example of a four-cylinder engine model with direct injection, a high pressure fuel pump and hydraulically-actuated variable cam timing with full multi-body mechanics running on a dynamometer. This type of simulation can originally have up to 195,830 scalar unknowns, and the same number of scalar equations. Once translated and compiled after symbolic manipulation, this reduces down to only 73 scalar continuous time states and 19,484 scalar time varying variables.

'It is important not to get confused between symbolic manipulation and automated model reduction,' says Claytex engineering director, Alessandro Picarelli. 'The former rearranges the equations to make them easier to solve, without changing the physical details within the model. The latter is where you start with your original detailed model and run a function, which reduces the amount of detail in the model, so it becomes less predictive, but runs quicker.'

Chemistry cluster

As well as manipulating algebra to improve efficiency, the way in which the simulation is computed can also be manipulated to run faster. For example, chemistry clustering is one way to speed up combustion simulations.

If a set of cells experiences very similar conditions, such as pressure, temperature, A/F ratio and amount of EGR, these cells are put into a group. Chemical reactions are then solved for the group rather than for each individual cell. This saves valuable computing time.

'The result obtained for the group represents the result for each cell in the group,' explains Suffa. 'But as you are solving reactions on the level of groups, the required resources will be significantly lower compared to solving them per cell, which is also similar to In-Situ Adaptive Chemistry Tabulation. Here the reaction chemistry itself is reviewed for relevance at each iteration. Irrelevant parts of the mechanism are not solved. Again this helps to minimise the computer resources used.

'Another promising technique is in-advance tabulation of the reaction kinetics, where one separates the solution of the flow and the solution of the reaction chemistry,' Suffa adds. 'The reaction mechanism is solved for a limited number of conditions ie combinations of pressure, temperature, EGR and Lambda, which are expected to occur in the flow domain. The outcome is a multi-dimensional table containing the combustion results. During the actual CFD simulation this table is continuously being searched through trying to match as closely as possible the tabulated conditions with those obtained during the CFD simulation for each individual cell. For very large mechanisms applied to large computational grids this technique offers tremendous speed ups.

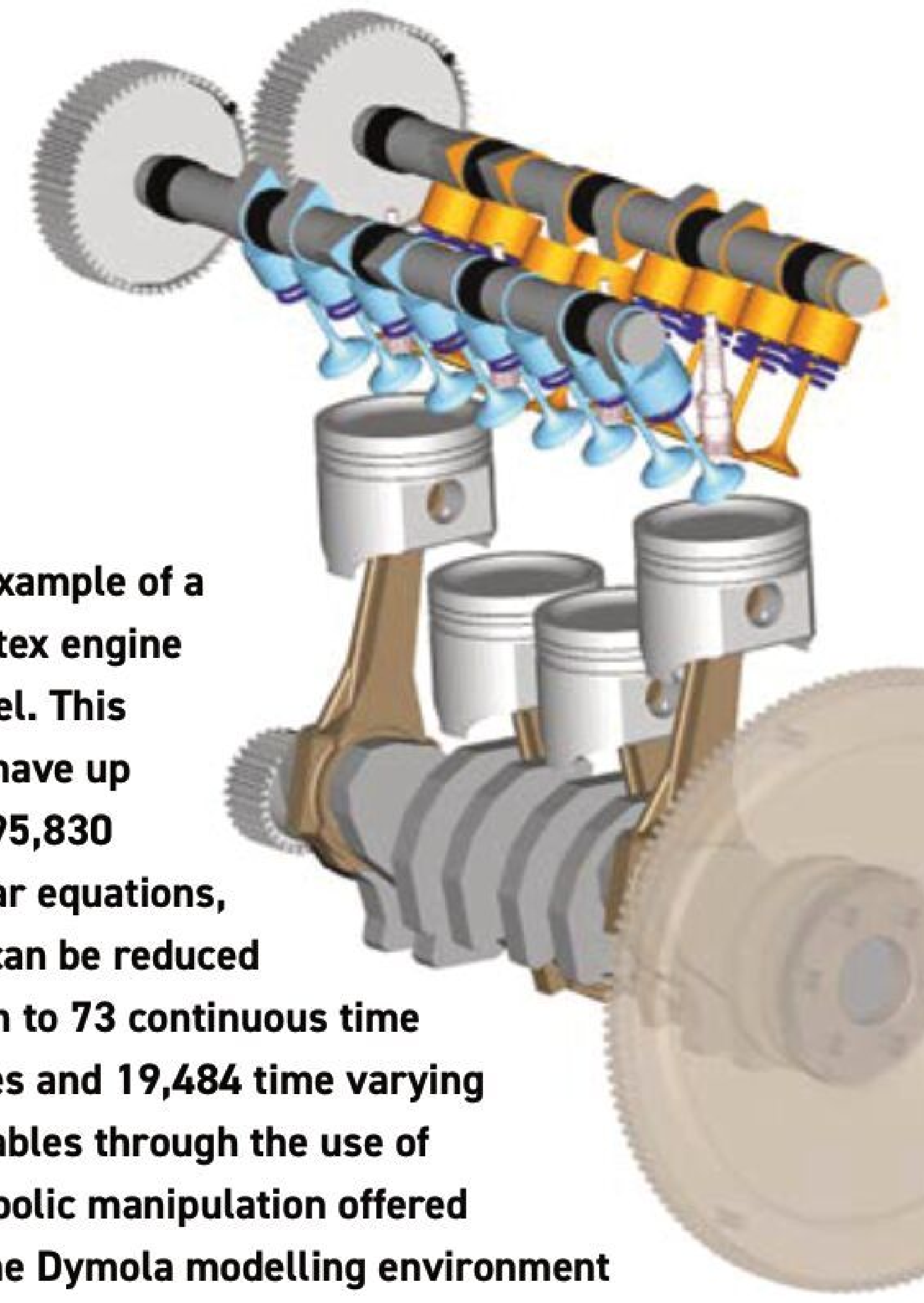
> **» 'The trick is to reduce the number of equations without eliminating any of the details in the model'**

'But this is not the end of the line,' Suffa continues. 'I expect in future the utilisation of Graphics Processing Units (GPUs) for solving reaction chemistry. This has the potential to further speed up combustion simulations.'

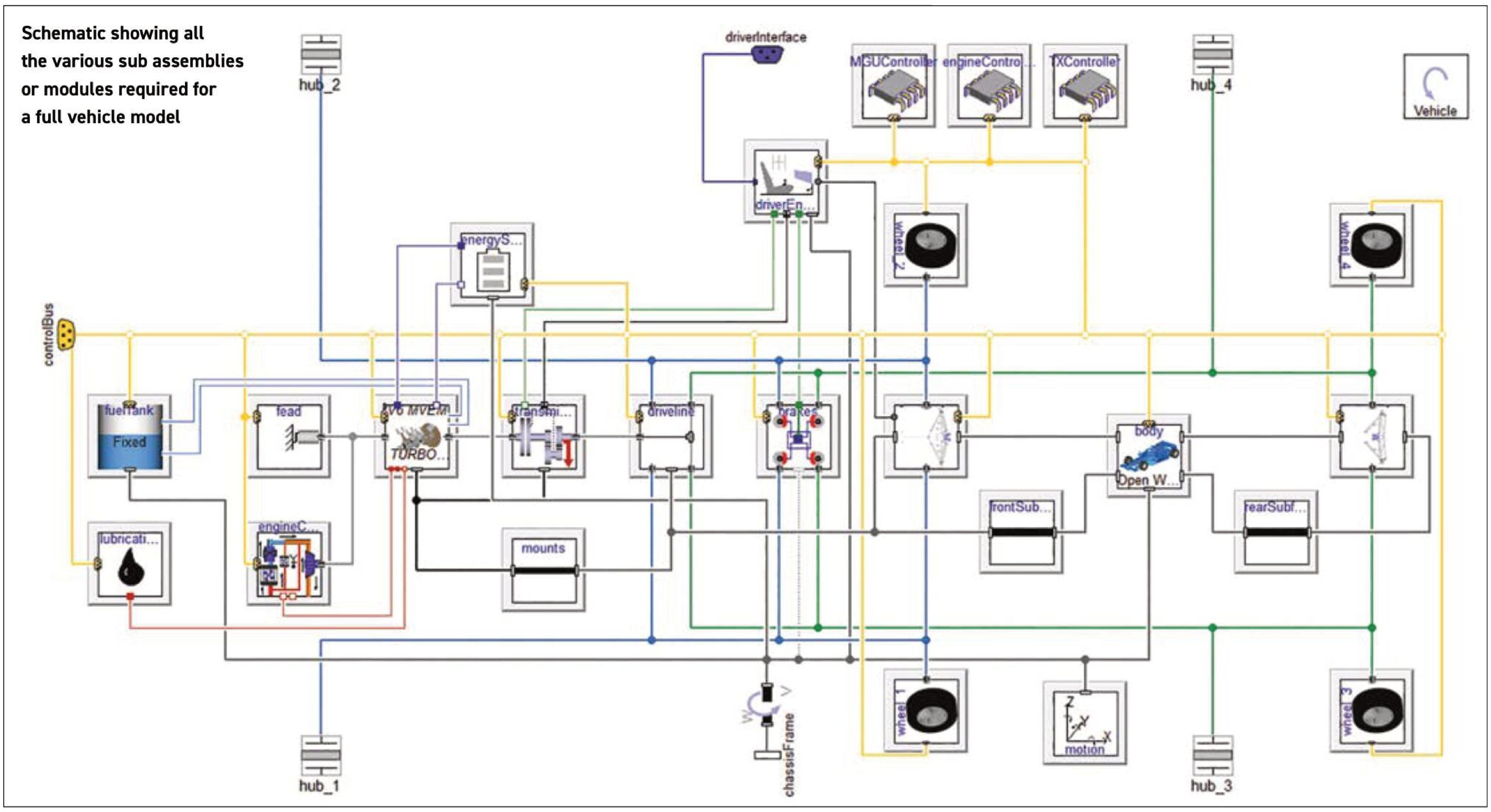
The future

The current limitations in computing power mean it is still not possible to solve DNS (Direct Numerical Simulation) without the use of models. 'The modelling comes in when you start to simulate flows that involve turbulence,' says Senecal. 'Currently, we can't achieve the required resolution on today's computers and so we can't resolve all the turbulence scales within the system, but we can resolve some, and model the rest. The most common way to do that is use the RANS (Reynolds Averaged Navier Stokes) and k-ε type turbulence models which are the workhorses of engine CFD. However, more people are starting to use LES (Large Eddy Simulation), which is a compromise between RANS and DNS, where you use a finer mesh but you're still not resolving everything. The increased resolution of LES makes it more realistic, but also more expensive.

'As computers get faster, the number of processors increase and codes become more scalable, we can start to run bigger problems, making LES more feasible,' concludes Senecal. 'Maybe in 10 years' time we will see it become more mainstream.' But will there be another revolution in simulation technology in the meantime?



An example of a Claytex engine model. This can have up to 195,830 scalar equations, but can be reduced down to 73 continuous time states and 19,484 time varying variables through the use of symbolic manipulation offered by the Dymola modelling environment

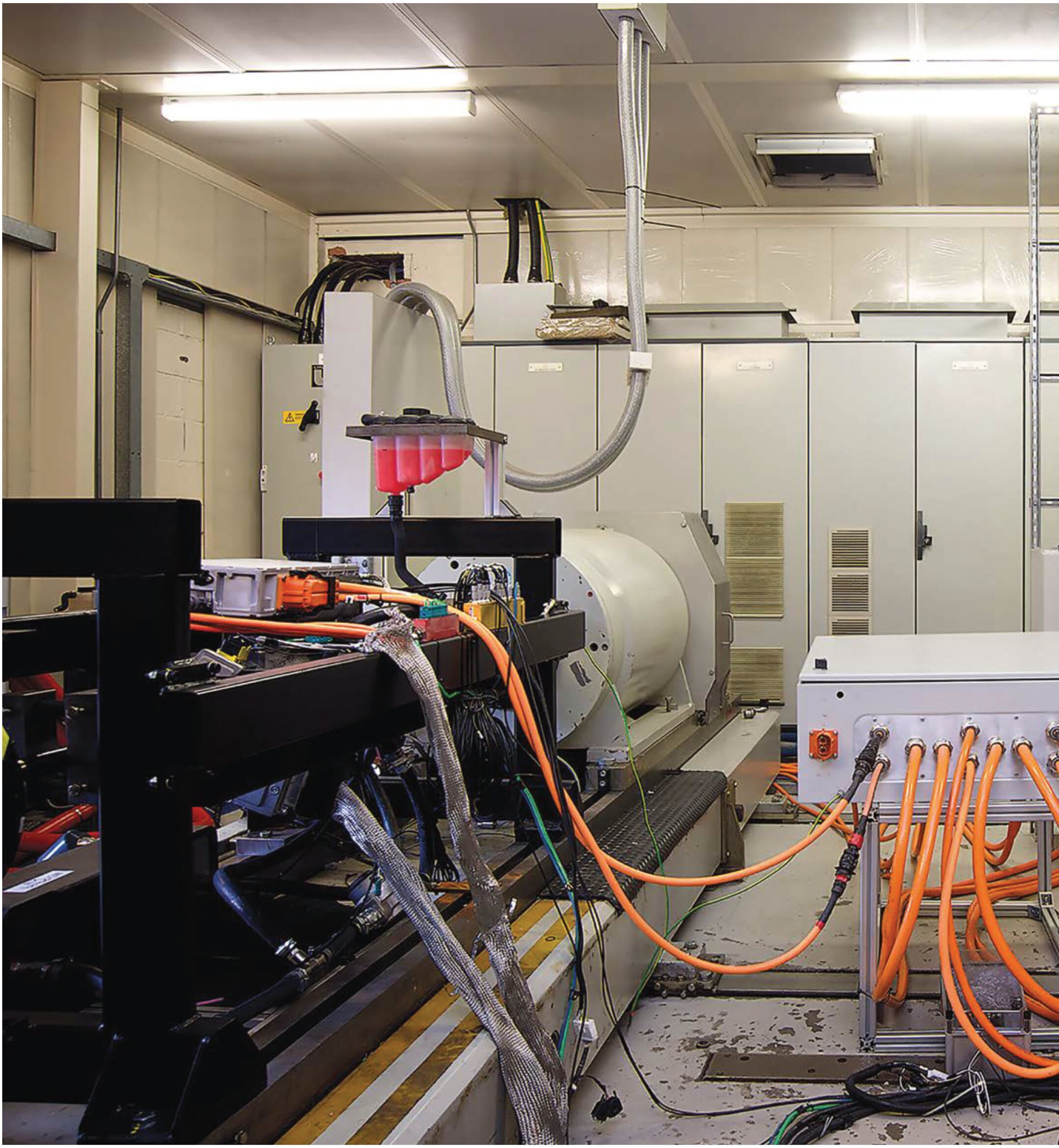


Schematic showing all the various sub assemblies or modules required for a full vehicle model

The rise of the dyno-saurs

Ricardo explains the latest developments in dynamometer systems for the motorsport industry

By Stewart Mitchell



Ricardo

Engine dynamometers are systems used to measure the performance of a powertrain. They allow engineers to characterise the performance and behaviour of engines in a controlled environment on a consistent base, rather than out on track where variables would make their work much more challenging.

Dynamometers come in many forms and are designated according to their modes of operation. The most basic are capable only of applying load in a single direction, and typically use water brakes or eddy current drives to apply that load.

The most sophisticated can apply and absorb load by the powertrain under test. These are often referred to as motoring dynos and use either electric motors or hydrostatic pumps. The ability to absorb torque allows input forces to the powertrain to be simulated.

Although torque output is critical in motorsport, in energy-limited formulae such as today's Formula 1 and Formula E, the drive for efficiency is paramount. Here, dynamometers are used as much for efficiency measurement and drive cycle testing as they are for tuning for outright performance.

James Sundler, business development director of performance products at Ricardo explains: 'If you take reliability, quality and weight as absolute givens in motorsport, what we're seeing now is a much greater focus on efficiency. When you consider series like Formula E, engineers strive for fractions of a per cent of performance improvement, particularly where so much of the car is restricted by regulation.

'Here, measurements with the greatest degree of fidelity at high drive speeds provide information on not only where to look for those fractions of a percentage point of efficiency, but also confirmation on the pre-test computational analysis, whether that's generated from gear micro design, differential configuration, bearing and seal performance or lubrication management.'

Electrified powertrain sub-systems are tested using simulation rigs that perform as the powertrain would in the racecar

Drive cycle testing

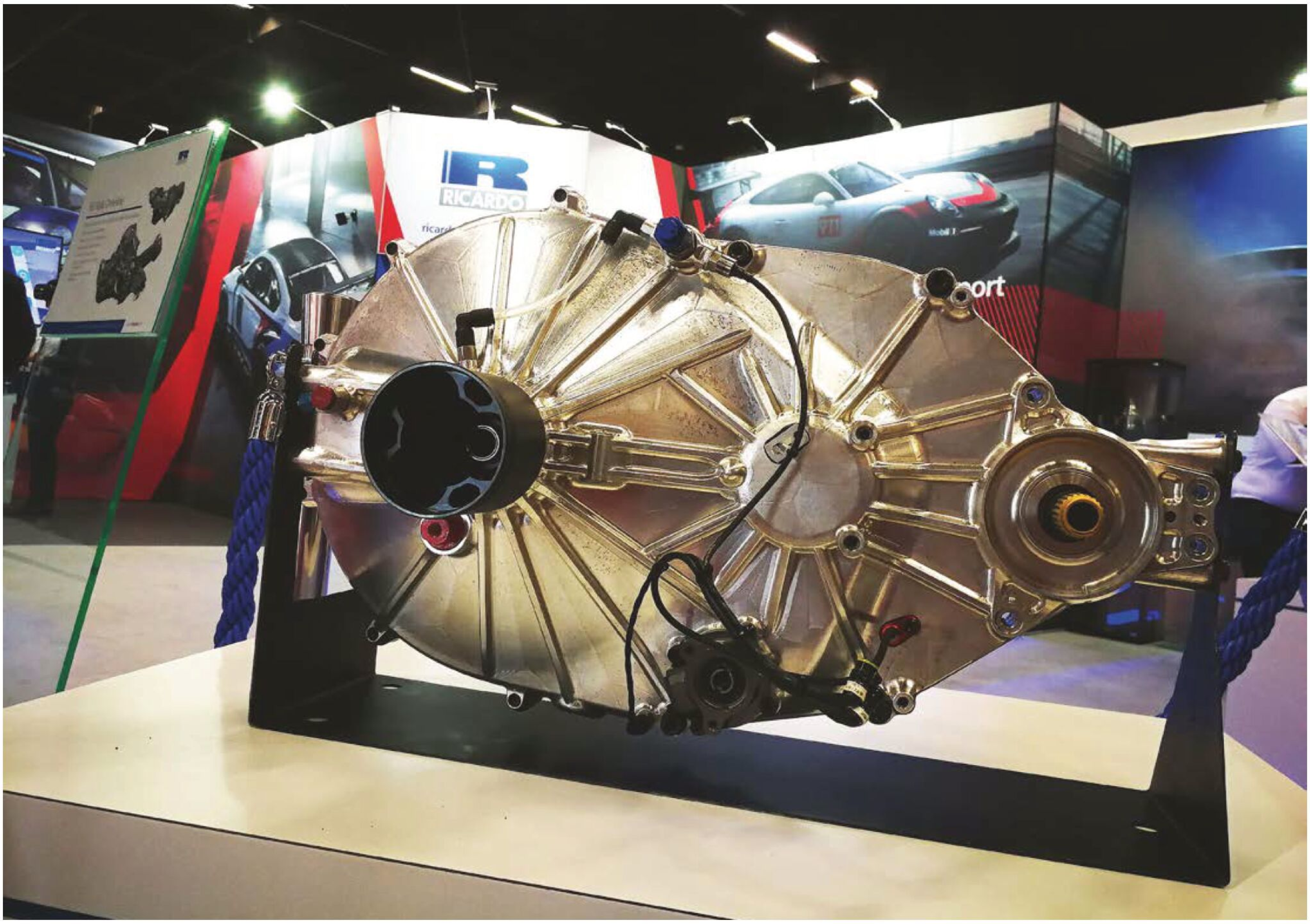
Drive cycle testing can accurately simulate powertrain loads under race conditions and, as such, is one of the most useful tools for development engineers in motorsport today. Engineers can use simulated data or real data collected during track testing in drive cycle testing to run life-like scenarios through the powertrain.

A driveline test facility can simulate the effect of all on-track conditions, including the correct throttle opening and closing timing and, with a vehicle model in the software, it can also generate a load representative of those caused by the mass of the vehicle and its aerodynamics.

Electric dynamometers can change the load rapidly to represent full throttle shifting, and load spikes generated from clutch release. They can also accelerate the engine with the throttle closed, as would happen during a downshift.

'Tests on the most sophisticated dynamometer systems range from the spin test for functionality of gear shifts systems,

» Dynamometers are used as much for efficiency measurement and drive cycle testing as they are for tuning for outright performance



Stewart Mitchell

Ricardo designed and manufactured the single-speed gearbox for the DS TECHEETA team, which twice won the Formula E constructors title

or to understand the spin loss of a system for efficiency at different temperature conditions, through to tilt rigs to understand the lubrication regime and the effect of cornering acceleration and deceleration,' says Ian de Souza, driveline test operations manager at Ricardo. 'Others include the loaded driveline rigs, which have a dyno for each of the driven wheels, whether two or four-wheel drive.'

The test cells

As dynamometer testing is essentially a scientific investigation, it must be in a controlled environment. As such, the construction of the cell within which the dyno sits is a lot more complicated than simply installing a basic HVAC system to ensure temperature and humidity remain stable.

Other factors must also be considered, such as the level of heat rejection from the powertrain, as even small IC engines radiate as much as half the output energy as heat into the cell from the exhaust, radiator and block surfaces. A test cell with the exhaust routed outside will require approximately 2000cfm of air-moving capacity per 100bhp of engine output.

Mimicking the flow and the tuned length of the sections of exhaust system as it will be on the car is vital to ensuring an engine on test is subject to similar back pressure levels as it would experience in the racecar. For this reason, the exhaust on the test bench is tuned using devices such as servo-controlled butterfly valves, to precisely replicate the pressure produced by a specific car's exhaust system.

Although heat rejection is less in an electric powertrain, the nature of their operation means the temperature window within which it efficiently operates is far narrower than ICEs.

De Souza concurs: 'Control of environment, and the accuracy of the measurement devices, are so critical for an electric powertrain. The key thing with an electric driveline system is because the efficiency now is so high that, in order to make improvements, you're looking at tiny margins, and therefore it is crucial to be able to quantify the effect of small developmental changes. That comes back to control of environment.

'The move to more electrified drivelines means we're seeing significant changes now in the architecture within the test facility. DC power supply in the form of battery simulation is critical in these test facilities. Additionally, significant investment has been made into the electrical measurement required to develop those systems. As an example, we are commissioning a very high performance, full powertrain rig that is capable of running ICE, hybrid and electric drivetrains. This four-wheel drive powertrain rig is climatic and capable of absorbing up to 1.25MW and can handle wheel speeds of up to 3000rpm.

'Depending on the rolling radius of the tyres, that's in excess of 200 miles per hour, and we can run that with electric input, engine input or combined drive.'

> » Control of environment, and the accuracy of the measurement devices, are so critical for an electric powertrain
>
> Ian De Souza, Ricardo

Instrumentation

Most dynamometers are supplied with sensors and a data management interface, including data analysis software. Typically, a single computer-controlled console is the only interface for the user. However, the more sophisticated the dyno, and the more parameters being investigated, the more sensors mounted on the powertrain and


KAISER®
RACE TECHNOLOGY
SOLUTIONS MADE OF PASSION
F1 RACE PARTS
WEC RACE PARTS
WRC RALLY PARTS
AERO SPACE PARTS

the more computing power is necessary to measure, log and tune parameters.

Powertrain speed, ambient air, coolant temperatures and pressures and fuel and air mass flow are all essential parameters, and are seen in any dyno system control interface. Racecars usually carry data loggers, recording parameters such as pressures, temperatures and throttle inputs, but on a test bed – free from the packaging and weight constraints of a racecar – the powertrain can be instrumented to a far greater degree.

For testing purposes, the sensors on the powertrain as it is installed in the race vehicle are often duplicated on the dyno. This is because the language of the data acquisition system on the engine as it is instrumented in the car may not be sophisticated enough to take accurate performance or tuning parameters from.

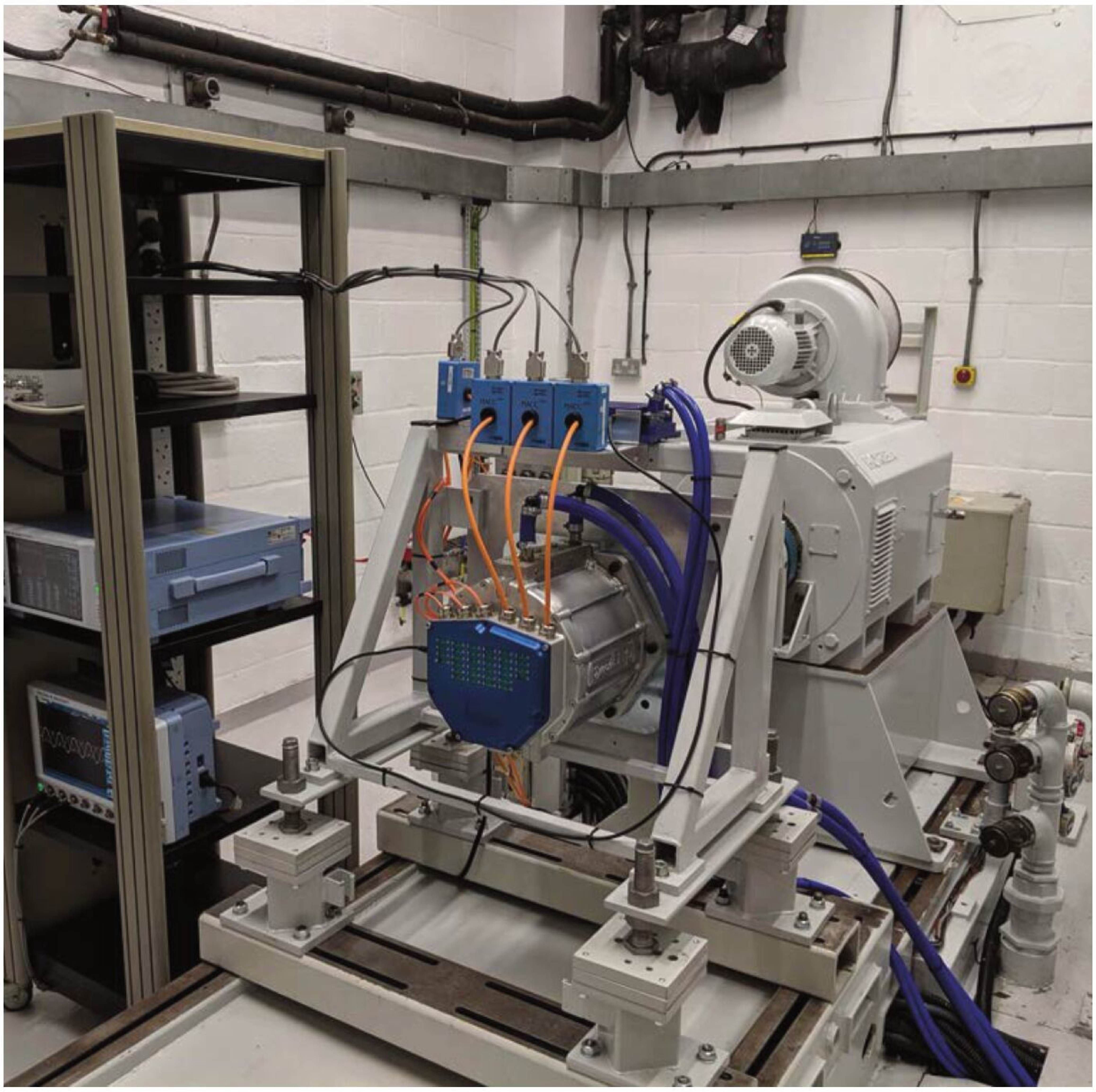
The number of required data inputs increases considerably when testing becomes more involved. As an example, measuring cylinder pressures requires a fully instrumented test bed with as many as 150 sensors. Depending on their role, sometimes these sensors are all recording and logging in real time for each phase of combustion, generating a visual output for the dynamometer operator.

'We continue to optimise the combustion system as we get closer to those last few percentage improvements,' continues De Souza. 'It really comes down to small development shifts in design and the engine management system. In order to be able to test and monitor those small changes, control of experiment is critical and high accuracy measurement with greater resolution is important.'

Digital and analogue signals are used in various ways depending on the tasks the engineers working on the engine want to achieve. Each analogue channel requires a signal conditioner to process its output before the data analysis system receives it. The reasons for using analogue vs digital vary, with some firms having their own reasons for a specific type of installation.

Increasing capacity is then just a case of implementing expansion boards, which can be daisy chained together with standard hardware. Additionally, the data analysis programmes

» Organising the mountains of data accumulated, and analysing it, can be the most challenging part of dyno testing


Ricardo

Ricardo's in-house designed and manufactured e-machine on test in the company's bespoke electric drive testing facility


Ricardo

The gearbox's lubrication regime is tested on rotating rigs to understand how it stands up to the *g* forces seen in racing

are also scalable, allowing users to create any number of channels and select the value of the data shown as a function of the powertrain performance parameters they are measuring.

Dedicated pressure, load cell and frequency inputs, as well as outputs for controlling components such as throttle servos, are typical inputs and outputs on these expansion boards.

Organising the mountains of data accumulated, and analysing it, can be the most challenging part of dyno testing, and here is where the useability of the analysis software package comes into play. In the best ones, information from different sessions can be overlaid for comparison, which allows for many distinctive channels to be arranged logically.

Complexity ramps up further still when it comes to electric powertrains, as De Souza explains: 'The calibration of an electric drive system is complex, and includes the control of the inverter and how power is fed from the inverter into the electric machine. The data capture and logging capability to be able to see what's going on at very high speed is absolutely critical, and only the latest data management systems available make that possible.'

Torque transducers

The primary measurement taken from any type of powertrain is torque output, and in current dynamometer systems this is done with torque transducers. These measure the torsional deflection induced by the applied torque, either by measuring twist angle or surface strain.

The twist angle method requires a portion of the dynamometer's output shaft to deflect under load. Toothed discs attach at opposite ends of the section being measured to allow the system to calculate the deflection.

Surface strain measurement typically sees piezoresistive strain gauges attached to a coupling connected to the output shaft. Stretching or compressing the gauges varies the electrical resistance, and this relates to the amount of force on the shaft.

However, for contactless measurement, some dynamometer installations use magneto-elastic torque transducers. These measure stress by sensing changes in the magnetic flux of a shaft, or the permeability of a magnetic flux path, and use a magnetising source and a sensor. They are typically made up of a thin ring of magnetic material attached rigidly to a shaft with a sensor that measures the angular direction and magnitude, or permeability, of the magnetic flux around that ring as torque is applied. Torque causing stress transmitted along the shaft changes the directional moment of the flux, rotating it in a pre-defined positive direction when the force is increasing and the opposite direction as the stress is reducing.

The non-invasive nature of their operation, which does not obstruct the torque flow from the dyno in any way, means they can be installed closer to the prime drive input than usual. That allows detection of transient torque peaks at a more comprehensive resolution than those typically registered with other torque sensors.

Magneto-elastic sensors also offer a frequency response in the order of 2-4kHz, higher than traditional strain gauges or optical sensors. Additionally, given that magneto-elastic methods are a non-contacting method for measuring torque, they have high durability and repeatability, so can distinguish even the smallest changes made to the powertrain tune.

Perhaps unsurprisingly, as the trend in power units shifts towards electric, so measurement techniques have changed.

» The primary measurement taken from any powertrain is torque output, and in current dynamometer systems this is done with torque transducers

Ricardo

Dynos can be configured to test components individually or asses the operation and performance of entire drivelines

'In the electrified powertrain space, the transducers used for torque measurement must rotate at significantly higher speeds,' says De Souza. 'If you have a very efficient system, the delta between input and output power is very small. At low torque conditions, the accuracy error becomes more amplified, therefore you must have very accurate transducers. This is something the measurement unit manufacturers have been working very hard on over the years, and they're continually coming out with higher accuracy, more robust, higher speed devices.

'The rotating test hardware for Formula E motors is often spinning at around 30,000rpm so that comes with significant challenges because we need to constrain this mass. We're now starting to move right up to the limit of technology, not just on the measurement devices but also in the way that we hold them when we spin them that fast.

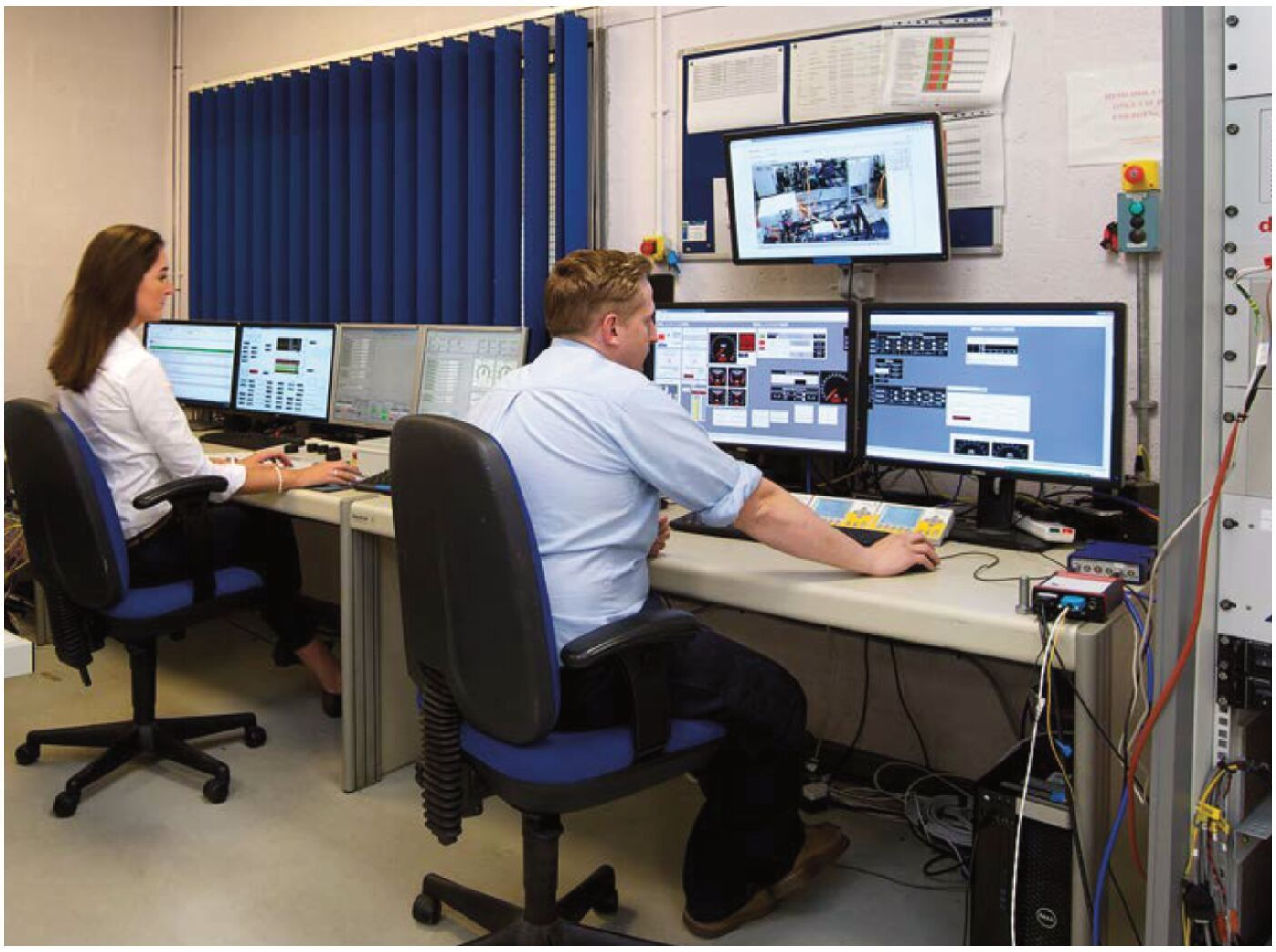
'The torque transducers we use for electric drives are flange type, where we can couple them directly to the input of the driveline and downstream where the wheels would be. They are a rotating flange with Wheatstone bridges inside them, and they measure strain. There is a transmitter within the rotating part, a receiver ring that sits around the outside of it, which is inductively energised. The ones we use typically have a 0.03 per cent or higher accuracy.'

Recent developments

Computing power has increased the capabilities of dynamometer operations, and data systems can log more channels of information at ever-increasing speeds. High-speed data capture is critical for the likes of electric drives and high revving, direct injection petrol engines, which rely on fuel injection timing accuracy down to less than a degree of crankshaft rotation.

Vast amounts of data capture in such short time intervals are vital for effective calibration. For example, a sample rate of over 2kHz is needed for combustion pressure sensors that must sample data to a logger several hundred times during the firing stroke.

Understanding cylinder-to-cylinder interaction is also necessary for efficient operation. Should a four-cylinder engine be on test, for example, each cylinder will be instrumented in such a way that it is possible to assess the performance and interaction between each one. A minimum of four channels feeding the data acquisition system, which itself must be capable of receiving data at a high rate, will be used for such an operation. Within each channel, the logger will log engine position concerning that cylinder, temperature and pressure sensors, along with injection timing and valvetrain position data.



Ricardo

Although many powertrain operations are managed automatically, controlling the scientific tests and analysing the vast quantities of data generated from them remains the domain of highly skilled engineers

The increased bandwidth of the latest systems collects the data generated and the computers that process the data have seen giant leaps in the last half a decade. For race teams or engine development firms with sufficient budget, cloud-based processing of data in real time is used for complex tests that require the most analysis.

With an almost unlimited, user-definable set of parameters, engineers can take more track-generated and wind tunnel data to the dyno to optimise engine set-up in development cycles. The increase in density of data accumulated in the real world is then incorporated into engine simulation, which also enables full hardware-in-the-loop simulation. This means a power unit could be running on a dyno with real time throttle inputs a driver is putting into a driver-in-the-loop simulator anywhere else in the world.

Another recent development has been an increase in drive motor speed, meaning active dynos are now capable of unprecedented rapid speed changes. These high-speed motors allow for precise replication of engine load situations and more meaningful correlation between on-track and test cell results.

Additionally, the latest motor technology offers potential cost savings for dyno operators as some can now regenerate power absorbed into electricity that can be returned to the grid. With some dynamometers outfitted with electric motors rated at 1400bhp, that recovery ability is significant.

Conclusion

Despite today's advanced computer simulation programmes, dynamometers remain a vital testing and validation tool in powertrain design and development. Engineers can now replicate real-world conditions on an engine in a test cell to a level never before possible, and the ability to accurately represent on-track, and indeed on road, running conditions is more important now than ever with the relentless strive for ultimate efficiency.

Additionally, the complexity of the latest hybrid vehicle drivetrains in top-level racing formulae will see dynamometer use become even more prevalent as powertrain calibration and tuning extends well beyond the traditional way of merely maximising power and torque output.

De Souza concurs: 'Our testing capability allows us to interrogate data in much higher resolution than was possible just a few years ago. The rate of change of the technologies we're testing, and the acceleration in the amount of work and investment we've needed to meet that demand in electrified powertrain testing alone is huge.

'Motorsport test cells, whether contemporary or 30,000rpm Formula E, are now arguably some of the most advanced testing facilities in the world.'

> **» In the electrified powertrain space, the transducers used for torque measurement must rotate at significantly higher speeds**
>
> Ian De Souza, Ricardo


WARNING: MAX FLUID PRESSURE 20barg
flowSonic
sentronics
MADE IN THE UK
SENTRONICS.COM


CASCADIA MOTION

Powder keg

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

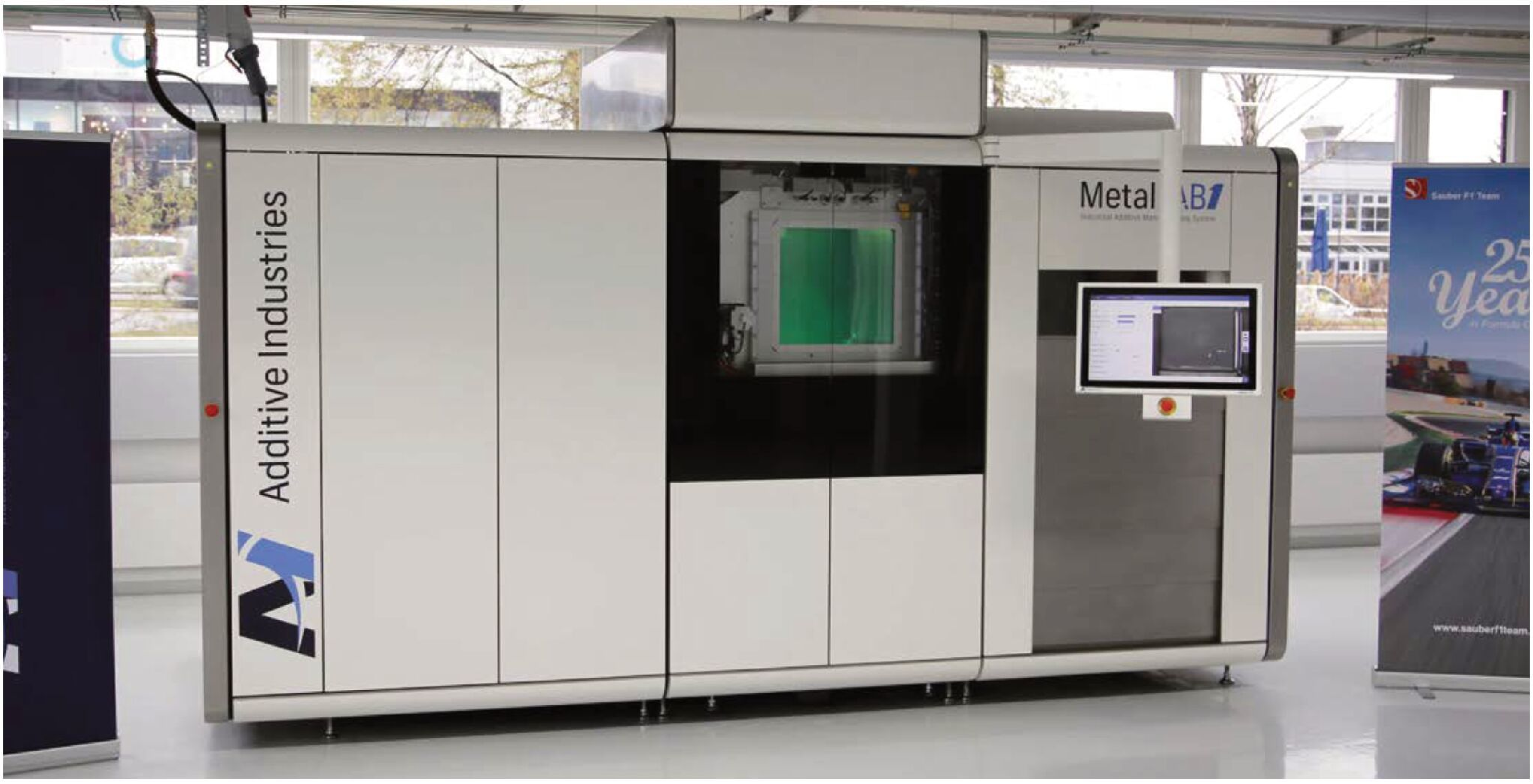
By LAWRENCE BUTCHER

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

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

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

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



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

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

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

Motorsport applications

For the purposes of this article, we will concentrate on the AM process most commonly employed for functional component production racing (see box out on p63 for a description of the various current AM technologies), powder bed fusion, both of polymers and metals.

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

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

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

Polymer processes

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

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

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

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

Metal processes

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

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

GRAPHITE
ADDITIVE MANUFACTURING

Beautifully engineered
3D Printing for motorsport

- Gain a competitive advantage
- Save Costs
- Save Time

sales@graphite-am.co.uk
graphite-am.co.uk 01296 482673

KINSLER

We did the Lucas metering for the Can-Am: 60's thru 70's; still do. Any injection: Road race, Sprint cars, Boats, Indy 500, NASCAR Cup, Drags, Motorcycles, Bonneville, Pullers, Street, etc. EFI, Constant Flow, Lucas Mechanical

Action Express Cadillac, '14, '15, '16, '17, 18, IMSA Champs. Overall '20 Daytona 24 Hrs.

Kinsler GT Porsche ITBs. We partnered with Ed Pink Racing Engines to design "Direct To Head" ITB package.

Super Vette, Riley Tube chasis, engines by Lee Muir. Ran Kinsler crossram manifold and Lucas mechanical metering.

Monster Mesh™ Filter
©

EFI Injectors, all makes of Pressure Relief Valves, and **Lucas Mechanical Metering Units, need 3 micron protection**, but 3 micron filters plug up too quickly, so most racers use10 micron, which is too coarse. We made this new element for NASCAR Cup cars: 10 micron premium paper top layer to take out 95% of the dirt, with a 3 micron precision Fiberglass lower layer. ***Details: Kinsler.com home page.***

10/3 Element

K-140 Pressure Relief Valve

Used on 95% of NASCAR Cup and INDY 500 cars

(248) 362-1145 Troy, Michigan USA sales@kinsler.com

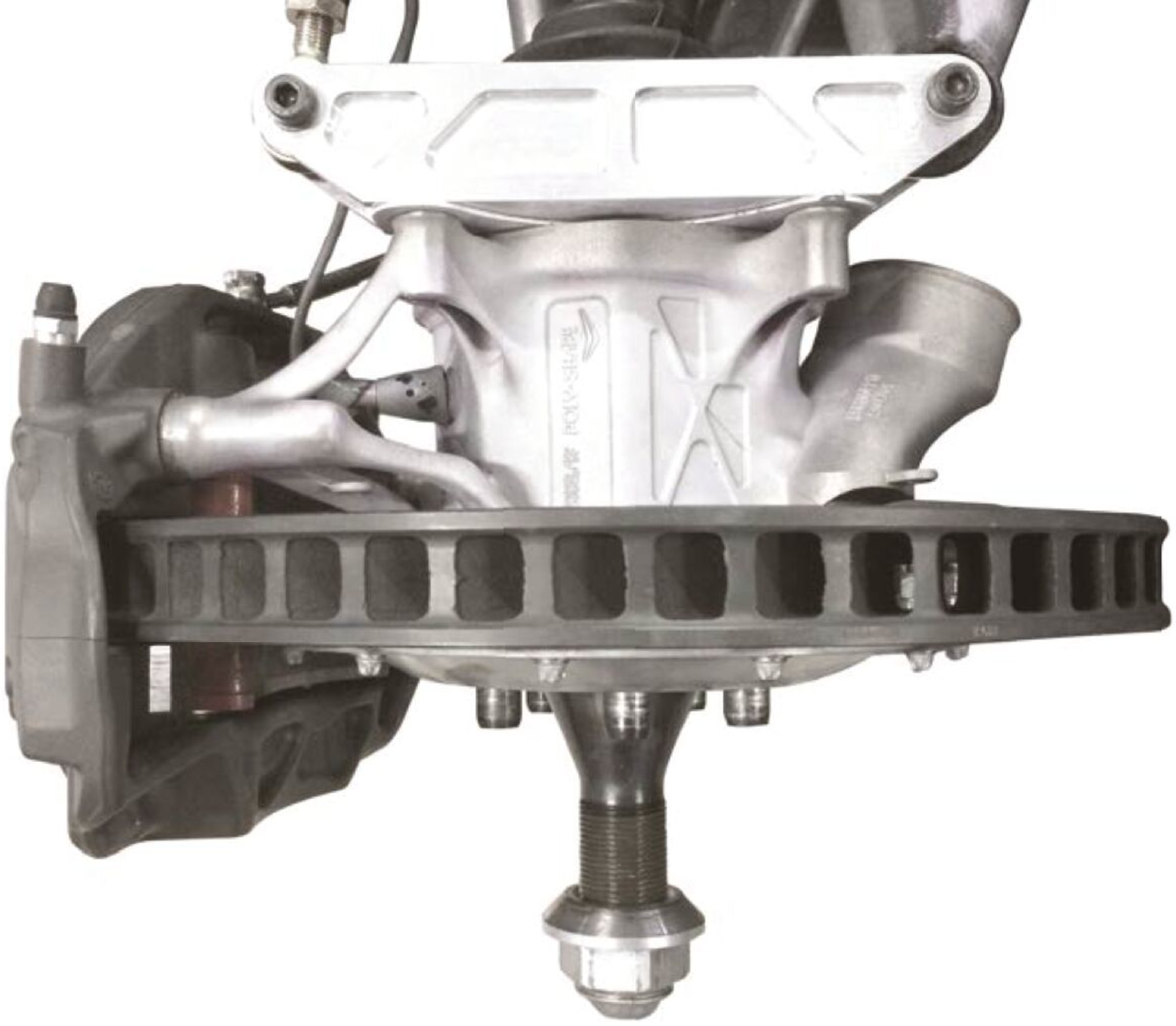
mezzo
TECHNOLOGIES

Mezzo designs and fabricates micro channel heat exchangers for a number of industries including automotive racing, aerospace and defense. **Mezzo's** products deliver superior performance in terms of increased heat transfer, reduced weight, and decreased volume. **Mezzo's** products are very damage tolerant, easily maintained, and reasonably priced. Products for the automotive industry include oil coolers, intercoolers, radiators, and condensers.

Mezzo is an approved supplier of radiators for IndyCar, and currently is involved most many high performance racing series such as F1, LMP1, etc. **Mezzo** takes pride in handling the toughest thermal management problems. Give us a call!

10246 Mammoth Avenue, Baton Rouge, LA 70814, USA
Tel: +1 (225) 442-6965 Fax: +1 (225) 706-0198

www.mezzotech.com email: kelly@mezzotech.com



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

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

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

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

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

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

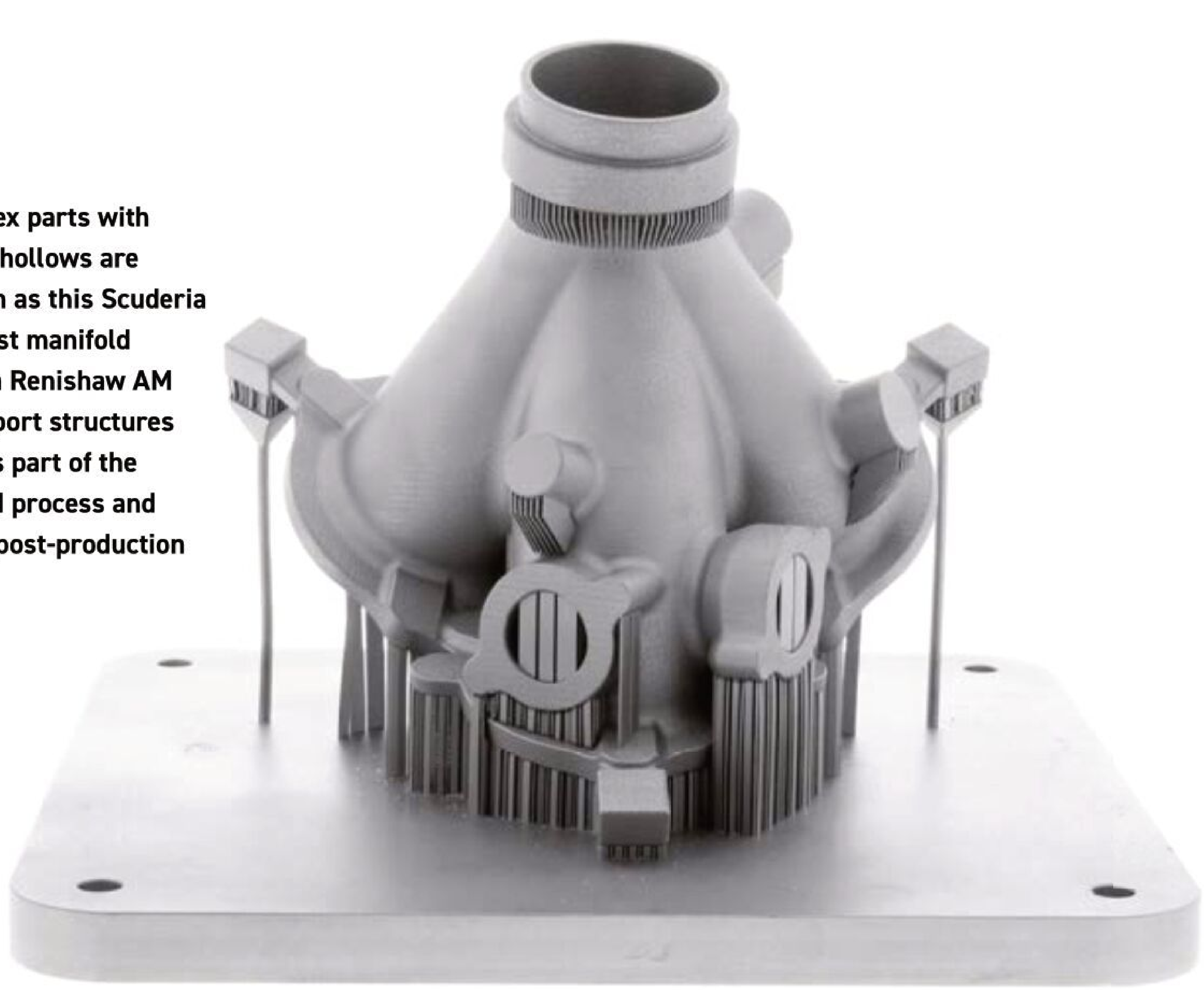
Post-production, the parts are heated in an oven to sinter the materials together. In this way the properties of parts can be precisely tailored, for example to maximise thermal or electrical conductivity in certain areas, or enhance wear resistance (the process can also deposit carbide).

Process control

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

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

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



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

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

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

AM technology categories

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

Vat photopolymerization

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

Material jetting

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

Binder jetting

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

Material extrusion

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

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

Powder bed fusion

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

Sheet lamination

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

Directed energy deposition

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

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

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

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

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

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

Design for AM

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

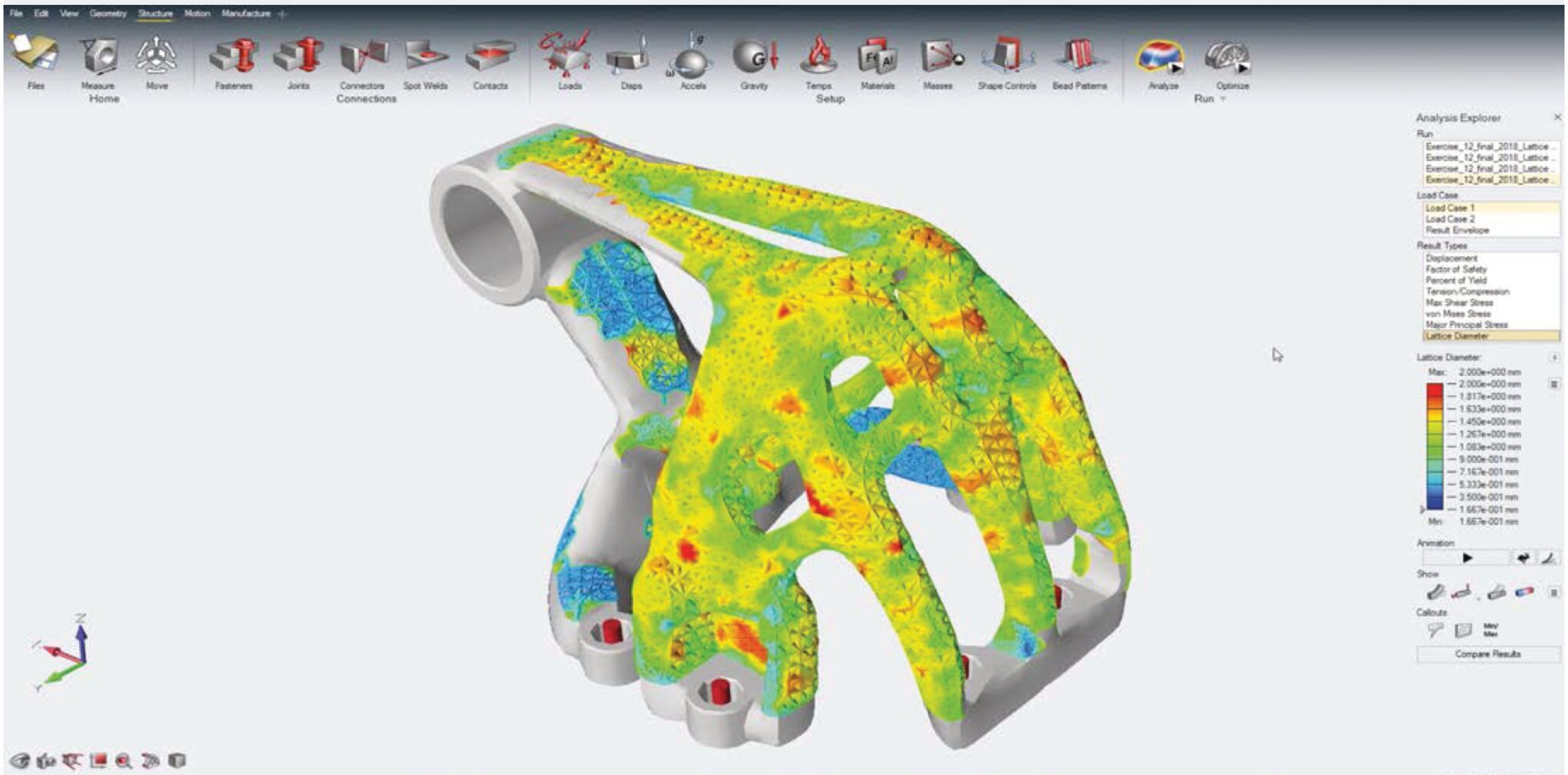
One example of the way AM changes the very philosophy of design is the lack of consideration needed for tool access or part fixturing, which is ever present when conceiving parts to be machined. However, there are a host of new factors that must be considered. Key amongst these are the potential for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

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

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

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

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



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

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

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

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

Optimisation

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

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

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

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

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

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

Future potential

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

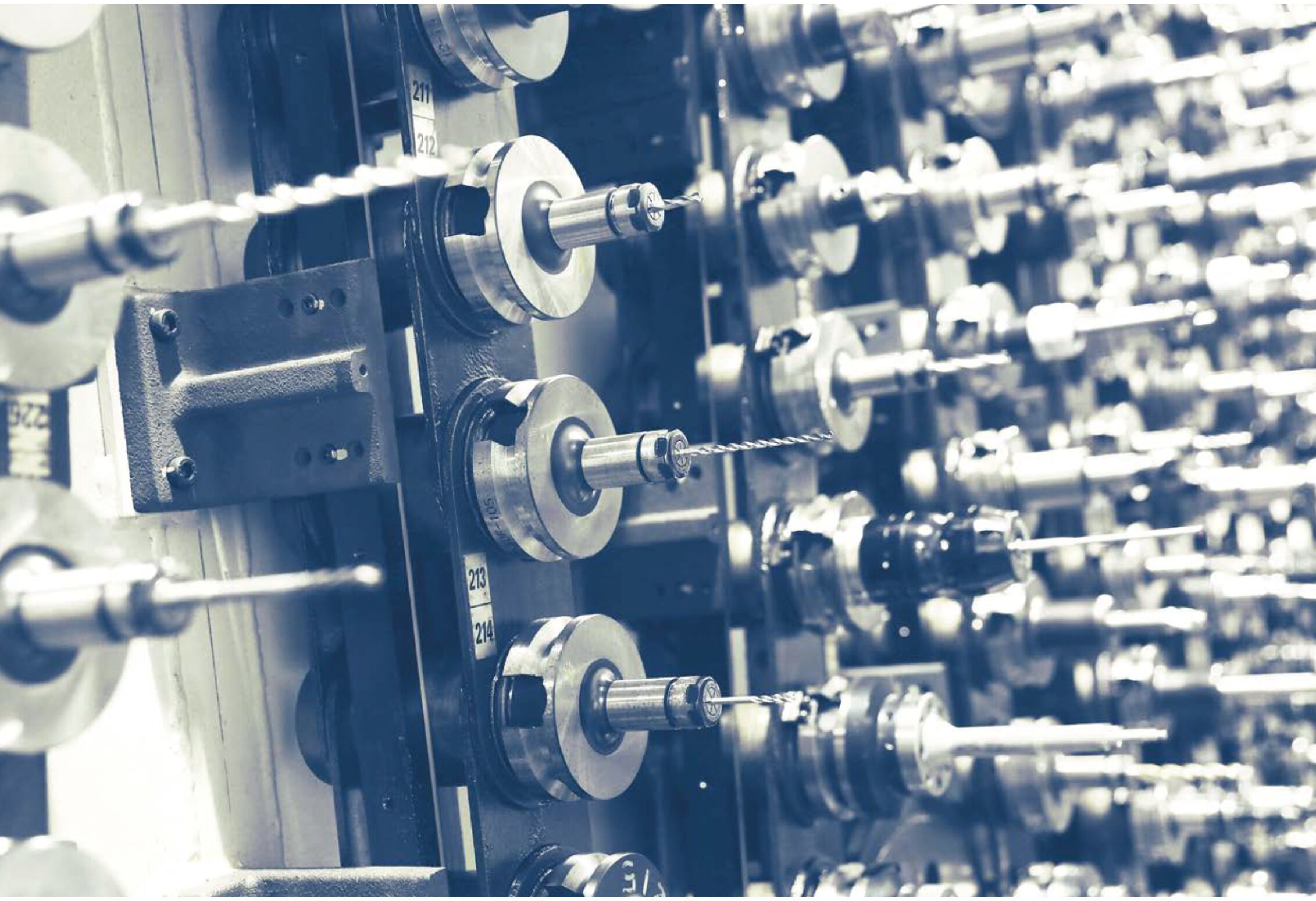
Elsewhere, there is also research underway into AM processes that can incorporate electrical circuits into parts, opening up a host of possibilities for integrated functionality within components. Ultimately, the true potential of Additive Manufacturing is only just becoming apparent, and its use will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

Automation station

Today's machining industry is shifting towards automated technologies to minimise human intervention and increase accuracy. *Racecar* investigates the engineering behind this trend

By GEMMA HATTON

GIBSON TECHNOLOGY



Tooling carousels can hold hundreds of types of tools, which the machine can automatically load when required. This minimises operator involvement while reducing downtime

> » 'The operator can just tap a few icons and the software writes all the complex code in the background, without them even realising it'

A modern Formula 1 car consists of up to 80,000 components, all of which have been machined at some point during their manufacture. That's before counting the number of re-designed or replaced parts, or prototypes and spares that never actually make it onto the car. Hundreds of thousands of individual components come together to create the racecars of today and producing this quantity of parts, along with their rapid development cycles, is only made possible by machines.

Machine technology is not only becoming more accurate and reliable, but the results more repeatable. Unfortunately, to achieve that, machines are removing the human element from the process because *we* are not accurate enough any more. Human error is one of the biggest challenges facing the machining industry today, which is why companies are shifting towards automation.

However, automating these complex machining processes whilst maintaining accuracy is an extreme engineering challenge.

'Everyone in the machining industry at the moment is talking about IOT (Internet of Things), there is a real push for more integration, automation and software-based solutions,' explains Mark Terryperry, applications engineer at US-based company, Haas CNC. 'Our next generation of controllers are built with better networking capabilities, which makes them easier to integrate with robots so that the machines can run lights out. Also, we can access the machines from our desktop, so as I'm talking to you now I'm looking at the status of my machines on my laptop. These are innovations that just weren't possible a few years ago.'

Birth right

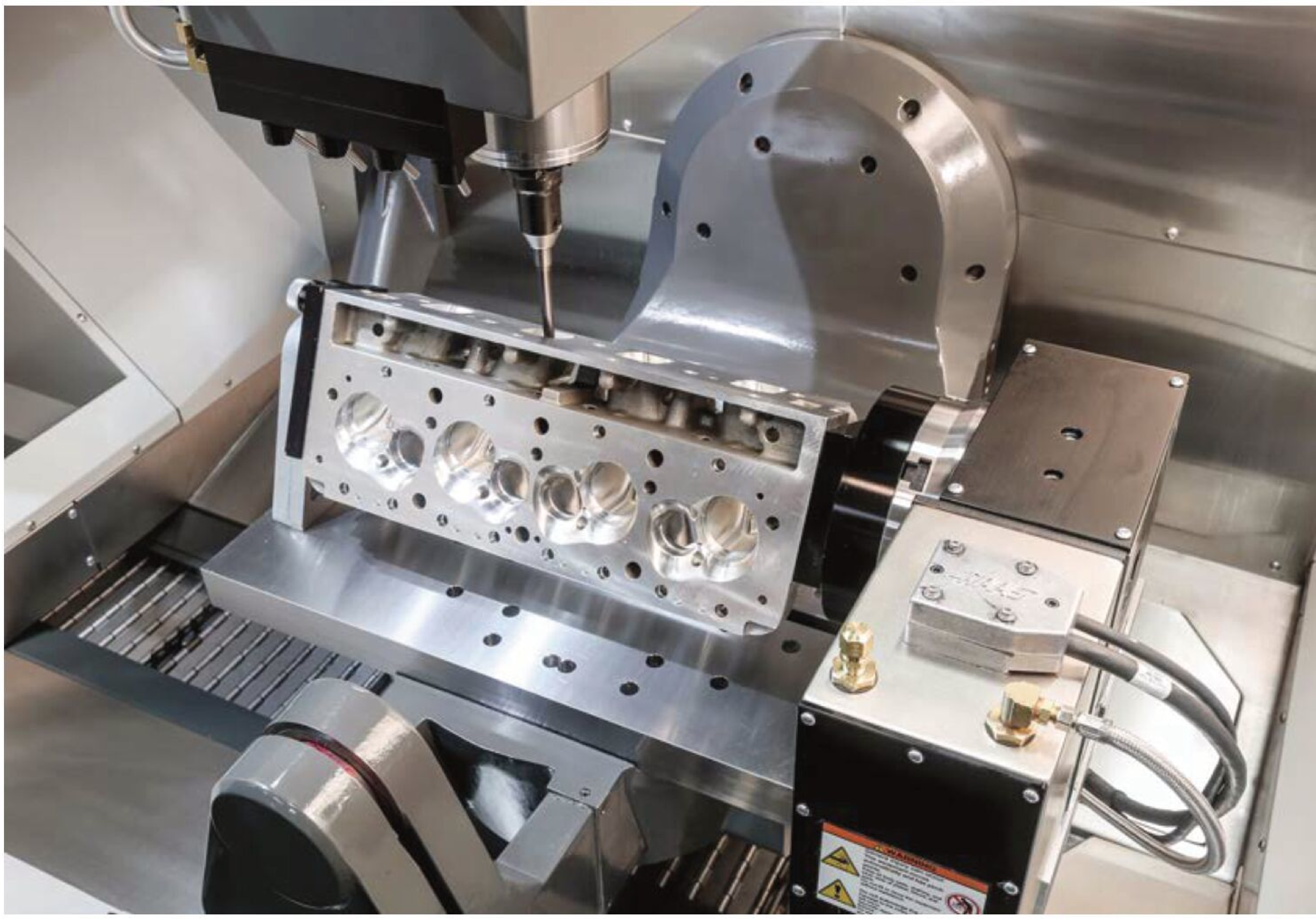
A part is first born in the virtual world of CAD (Computer Aided Design) software as a solid model. Once created, CAM (Computer Aided Manufacture) is used to translate the dimensional information of this solid model into a language the machine can understand. This code automatically defines the required tool paths, when to change the tool, as well as the sequence of machining processes required to manufacture the part. The software then controls the machine to carry out the processes via CNC (Computer Numerical Control).

Before, during and after manufacture, CMM (Coordinate Measuring Machine) plays an important role. This is where various types of measurement systems, usually in the form of probes, are constantly measuring the dimensions of features as they are being machined to ensure they are within tolerance. If not, this information is fed back to the machine, which can then account for any errors by automatically adjusting offsets.

'We have pioneered a software package called 4C, which combines all four of these types of control,' explains Anthony Usher, VP sales and marketing at Rottler. 'The result is a CNC machine that you can design things in, whilst eliminating the complex coding process because it's all done semi-automatically.

'Quite often, engine builders are scared of CNC machines because they're worried they will not understand the code, and will have to spend months learning how to program the machine. Therefore, to help them improve their accuracy and reliability, we have had to revolutionise the software to get CNC into their hands.

'I often equate it to the iPhone. In the past, you would have had to write complex code to get your 'phone to go onto the internet, or take a picture. When the iPhone came out, it had icons and apps that did the hard work in the background for you, so anyone could make a call. We have done the same with our machines. The operator can just tap a few icons and the software writes all the complex code in the background, without you even realising it.'



CMM (Coordinate Measuring Machine) uses probes, lasers and scanners to continuously monitor tolerances of machined features. This inspection process is fully integrated to ensure any errors are recorded and automatically accounted for

RAMTIC (Renishaw Automated Mill Turn Inspection Centre) consists of carousels that are plugged into each machine and automatically load the tools and materials. Up to 30 machines can be run by only two operators supported by kitting staff

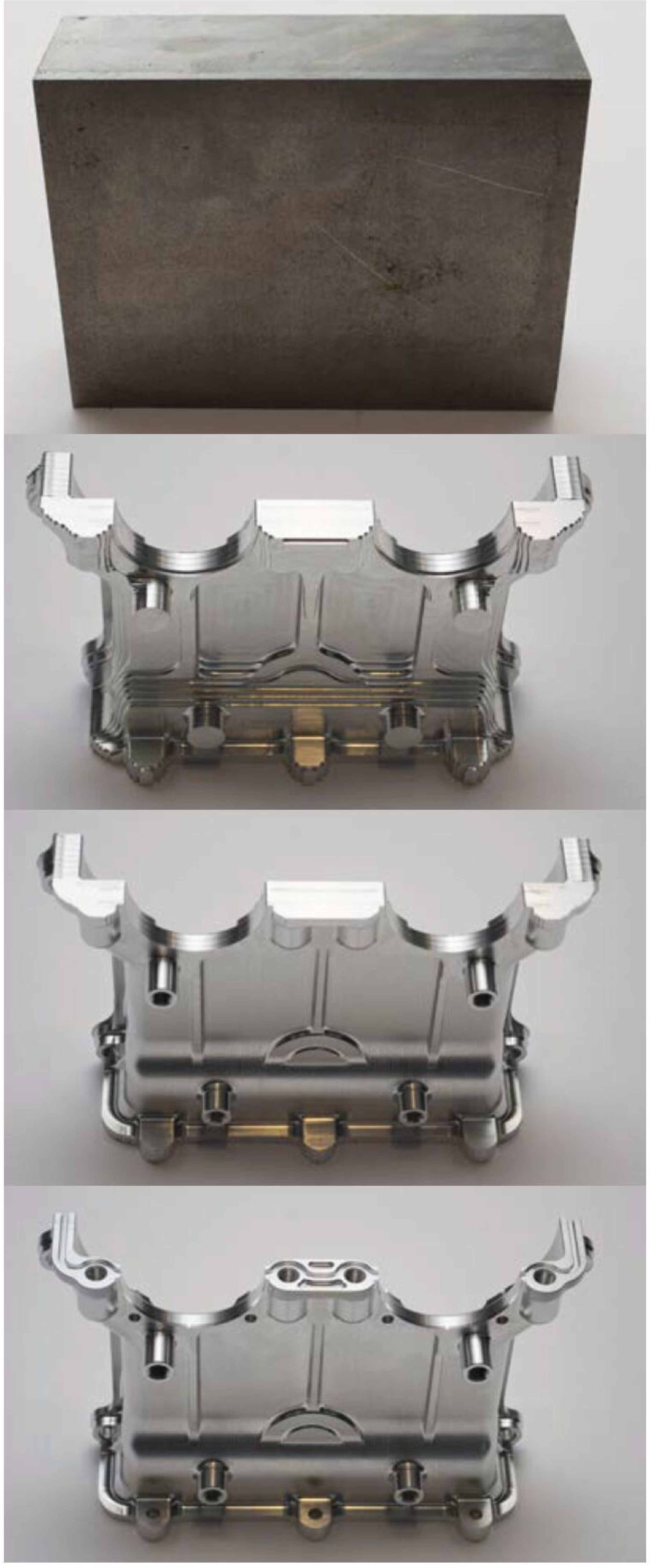
By automating the coding process, operators no longer have to spend days learning how to write code. All they need to know is the design they want and a quick guide how to tell that to the 4C software, and they can begin machining.

'Take the example of porting cylinder heads,' highlights Usher. 'Traditionally, operators destroy their hands and knuckles from the consequent vibrations of continuously holding grinding tools, but this is completely avoided with our 4C software. We use digitising, which is where our Renishaw probe automatically measures the inner and outer dimensions of the ports, and then converts this into a digital format that is displayed on the machine's screen. The operator can then use the mouse to draw the exact shape of the ports they want, hit 'cycle start' and the machine takes over. Within minutes, the port is finished exactly how the operator would have done it by hand. So, not only is the operator able to use their knowledge and experience to create the best port design, but the machine does it automatically, so they don't have to learn any of the code.'

Time lord

Time is money, and if there's one thing a manufacturer wants to avoid in their machine shop, it's downtime. This is when the machine is either off, or idling, and not producing parts. Downtime can be a result of maintenance or

» Carousels capable of running for 72 or hours or more without any human involvement, the next task to automate is part and tool setting



Five-axis machines have the capability to machine a part from start to finish, creating intricate shapes out of a billet of material

repair, but also between processes as materials and tools are loaded into the machine. One of the best strategies to minimise this is the unique RAMTIC (Renishaw Automated Mill Turn Inspection Centre) system developed by Renishaw who use it for their own manufacturing processes.

'Tooling carousels are pre-loaded with the raw material and tools for the job,' explains Anthony Spill, production engineer at Renishaw. 'This is done offline while the machine is still running so, as soon as the machine finishes, the old carousel is disconnected and the new one 'plugged in'. The machine identifies the carousel number and therefore all the components it has. All the operator then has to do is press 'Go' and the first wing of material is automatically loaded into the machine. The beauty of this system is we minimise downtime so, for 30 milling machines, we only need two operators, supported by kitting staff, to run them.'

It's not just one carousel per job either. Each carousel can contain enough material and tools for up to four different jobs. With so many components, it is essential to ensure that not only are the correct ones loaded, but that they are located in the right place and in the correct orientation. Empty carousels are plugged into a system at the re-kitting station where software automatically calculates the amount of material required, along with the tools needed, for the different jobs. All the operators need to do is physically pick up the pieces and populate the carousel, like a puzzle with instructions.

Life lessons

With each of these carousels capable of running for 72 hours or more without any human involvement, the next task to automate is part and tool setting. When working to tight tolerances, tool wear can greatly affect accuracy. The life of each tool is calculated and automatically tracked by software. This is the same software that dictates how to populate the carousels, and so will only recommend tools with enough life to complete the number of jobs. However, tool wear also needs to be tracked during machining, and this is done by the NC4 automated tool setter from Renishaw.

This system uses a laser beam projected between a transmitting and receiving head and, as the tool descends or moves sideways, it breaks the beam, allowing it to measure the tool geometry and the effective diameter whilst the tool is spinning, as well as any dimensional changes caused by thermal effects. Therefore, this system detects if the tool is within tolerance, or if there has been any damage.

3D vision

We have covered 3D printing technology many times in *Racecar Engineering*, but never on the large scale of a HP Jet Fusion 3D printing machine, of which XYZ Machine Tools is the official re-seller.

Delivering 30 million droplets per second across each inch of workspace, building at speeds of 4,500cm^3 per hour, this machine is approximately 10 times faster, yet half the cost of conventional material extrusion or laser sintering processes. This is thanks to HP's Multi Jet technology, which is then coupled with fusing and detail agents to generate layers just 0.07mm thick, creating parts with impressive dimensional accuracy and detail. Printing within such fine tolerances requires precise temperature control as the different layers fuse together. This is why heat is automatically applied or reduced throughout the different stages of the printing process.

The combination of all this technology results in a machine capable of creating 27,300 gear components within an 82-hour cycle, compared to 1,000 and 2,160 parts using other 3D printing techniques.

'Detecting tool breakage is absolutely critical,' explains Spill. 'The last thing you want is to have your operators come back to the machine after eight hours and find they've got eight hours of scrap components because the tool broke. When a breakage is detected, the machine alarms out, telling the operators there is an issue and it stops manufacturing. This helps us achieve minimal downtime because the operators can address the issue straight away.'

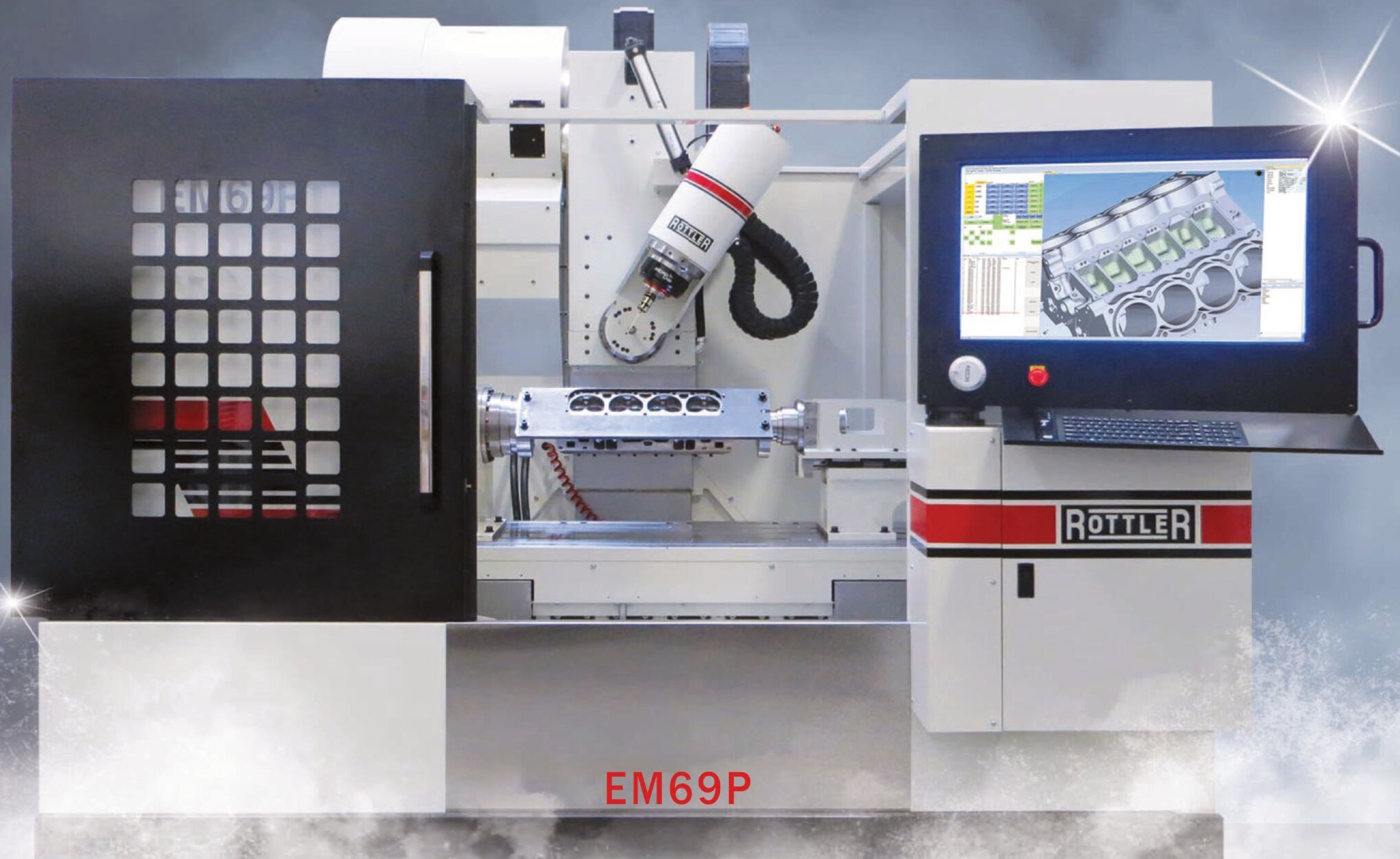
One of the ways to minimise tool damage is to use high pressure air or liquid coolant, which is channelled through the spindle and therefore applied directly to the tip of the tool. 'With non-ferrous materials such as aluminium, which are relatively soft, it's essential that we get any chips out of the way quickly so the tool doesn't load up and essentially weld itself to the material,' explains Terryperry. 'The coolant is a cutting oil so it's extremely slippery and provides great lubrication, whilst the high pressures of 300psi or 1000psi systems forcing debris away allow us to push the tools harder and faster.'

Keeping cool

Without coolant, the heat generated from the friction of machining processes would break the tools, regardless of their material hardness. Therefore, particularly for large volume manufacturing, it is vital to ensure the coolant doesn't run out. This used to be a responsibility of the operators. However, now it is down to sensors to detect when coolant levels become too low and switch on tanks to refill the coolant whilst the machine is running.

Despite the array of cooling strategies, tools still wear, and so do the mechanisms and fixtures within the machine as the machine gets older, which is yet another parameter that requires careful control to maintain high tolerances and accuracy.

'We check our machines annually with laser interferometry, but this is relatively time consuming to set up. However, you know the day after you've done the laser check


ROTTLER
ROTTLER
EM69P

> **» ‘Extensive integration between your five-axis machine, CAD, CAM, CMM and software results in the best blend of technologies’**

that the machine is accurate, but what about after several weeks?’ explains Andy Holding, marketing manager, CMM Products Division at Renishaw. ‘This is why we have the QC20-W ballbar system to allow us to quickly check the calibration of the machines.’

The ballbar is a telescopic bar that contains several precision machined magnetic balls, with cup joints at either end and an integrated position sensor. One end is attached to the centre of the machine table and the other to the spindle of the machine. This spindle follows a prescribed spherical path in all three axes around the centre point and, if the spindle position is out of tolerance along these paths, the magnetic balls will move and sense this change. This movement then induces a current within the position sensor and this signal is transmitted via Bluetooth to the machine. The results are then compared with the original calibration measurements and analysed to diagnose any machine errors that may require remedial or preventative maintenance.

‘Once the machine is calibrated, you can quickly use the ballbar to complete a trace of the ‘ideal’ working space. In the event of any collision or damage during machining, the ballbar system can be reinstalled and another trace can be conducted. By analysing the traces in software you can measure the positioning accuracy of the machine and identify the type and amount of any errors, which may be corrected by maintenance, or by adjusting parameters at a controller level,’ says Holding.

There is no doubt the biggest revolution in machining of recent years has come in the form of five-axis machines. Utilising their capabilities, together with advanced software and CMM, has resulted in an array of multi-tasking machines that can create solid models, convert them into code, calculate the required machining processes, complete them with absolute accuracy, monitor tolerances and tool wear. They are even capable of conducting the finishing processes and final inspection.

Complete package

‘Due to the complexity required by the motorsport industry, components are very high value, which means cycle times are extremely long. That’s why you need a robust process to ensure control throughout the entire machining phase,’ explains Lawrence McCann, UK applications manager for the Japanese parent company, Yamazaki Mazak. ‘Extensive integration between your five-axis machine, CAD, CAM, CMM and software results in the best blend of technologies. This allows one machine to not only carry out the manufacture of a component from start to finish, but constantly adjust itself based on an automatic feedback loop of measurements to achieve the highest tolerances, regardless of the conditions.’

There will always be some level of human intervention throughout the machining of a part, even if it is simple validation, but the amount of work carried out by operators has diminished rapidly in recent times compared to past practices. As the demand for volume and accuracy of parts increases in racecar construction alone, it is hard to see when, or how, this trend will reverse.

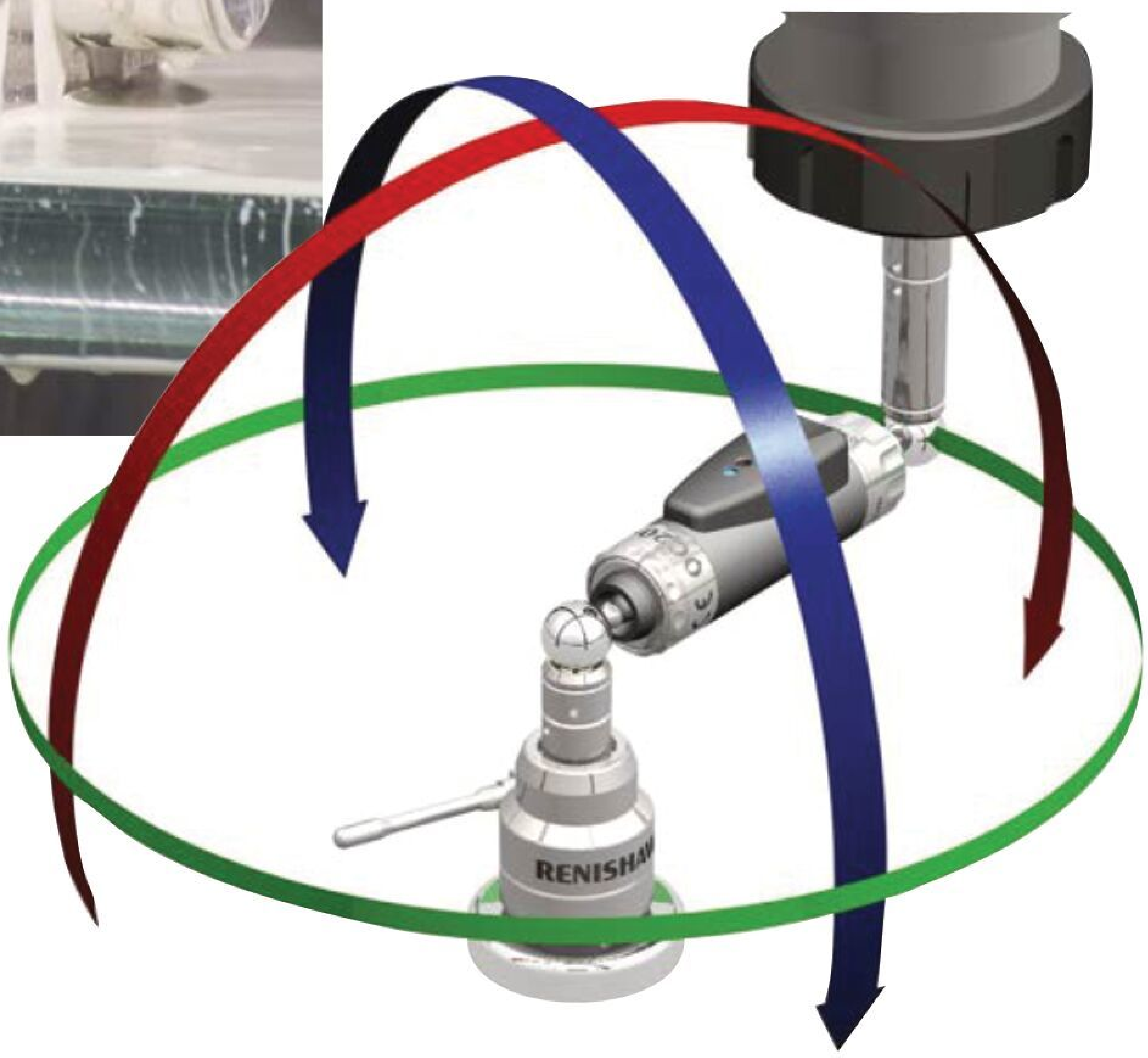
GIBSON TECHNOLOGY

Liquid coolant / cutting agent is blasted at 1000psi to the tip of the tool, reducing the temperature generated from friction and also removing swarf, which could otherwise weld itself to the part

Coating technology

Another strategy to increase both component and tool life is the use of coatings. These reduce manufacturing cost, while increasing the speed of machining processes, and maintain accuracy over time.

Carbon-based coatings, such as DLC (Diamond Like Carbon) are perfectly suited to the most extreme wear conditions and high sliding speeds. Oerlikon Balzers, a global technology leader for wear reduction coatings (the BALINIT and CAVIDUR families of coatings), is launching a new carbon-based coating that aims to raise the bar in high-end racing applications.

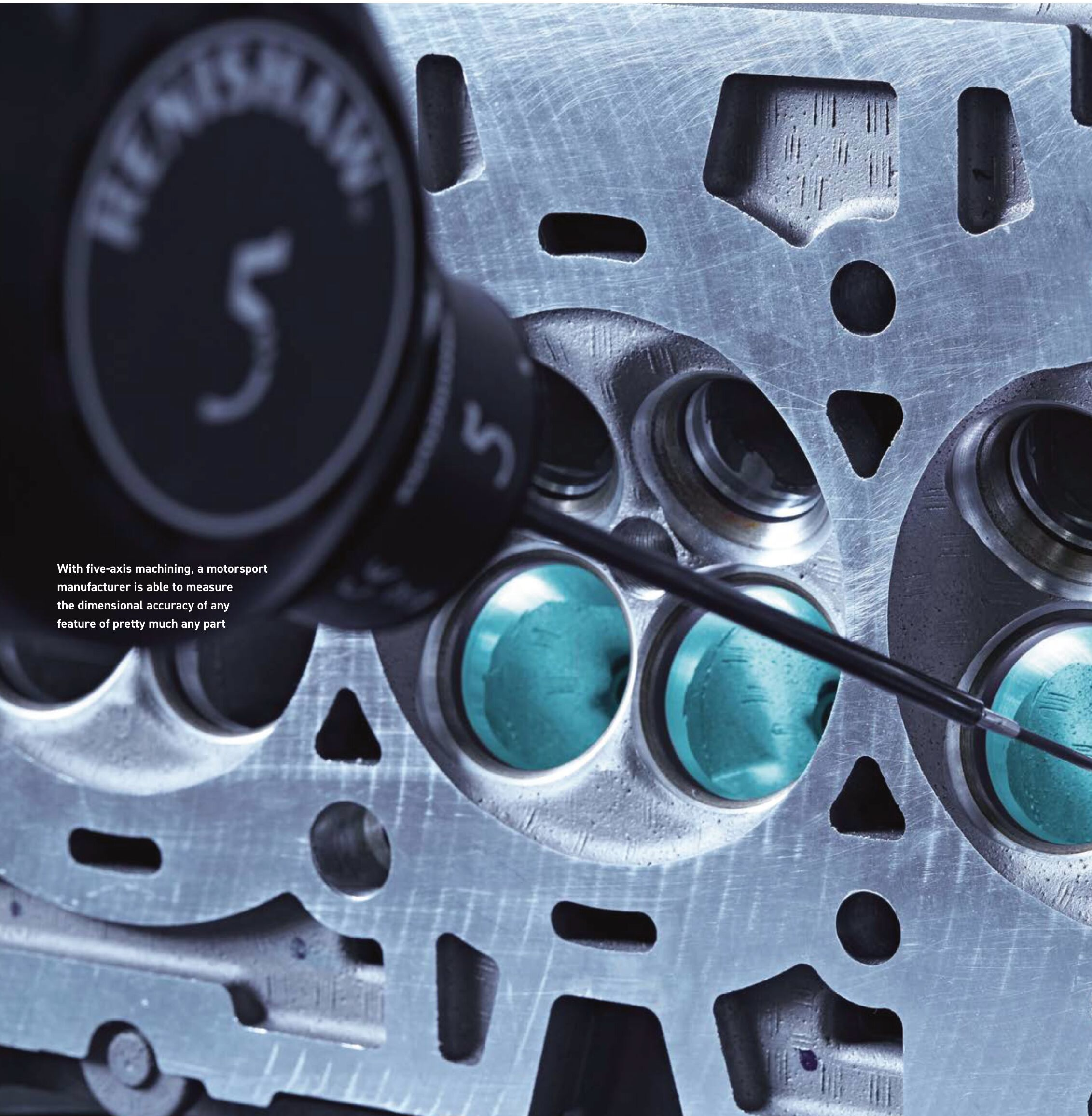


Renishaw’s ballbar follows a circular path in three axes to measure the working space of the spindle. This can be overlayed with the ‘ideal’ working space to calculate any machine ageing

For good measure

Micron-perfect dimensions are vital in motorsport and recent developments in metrology mean the industry is now achieving phenomenal accuracy

By GEMMA HATTON



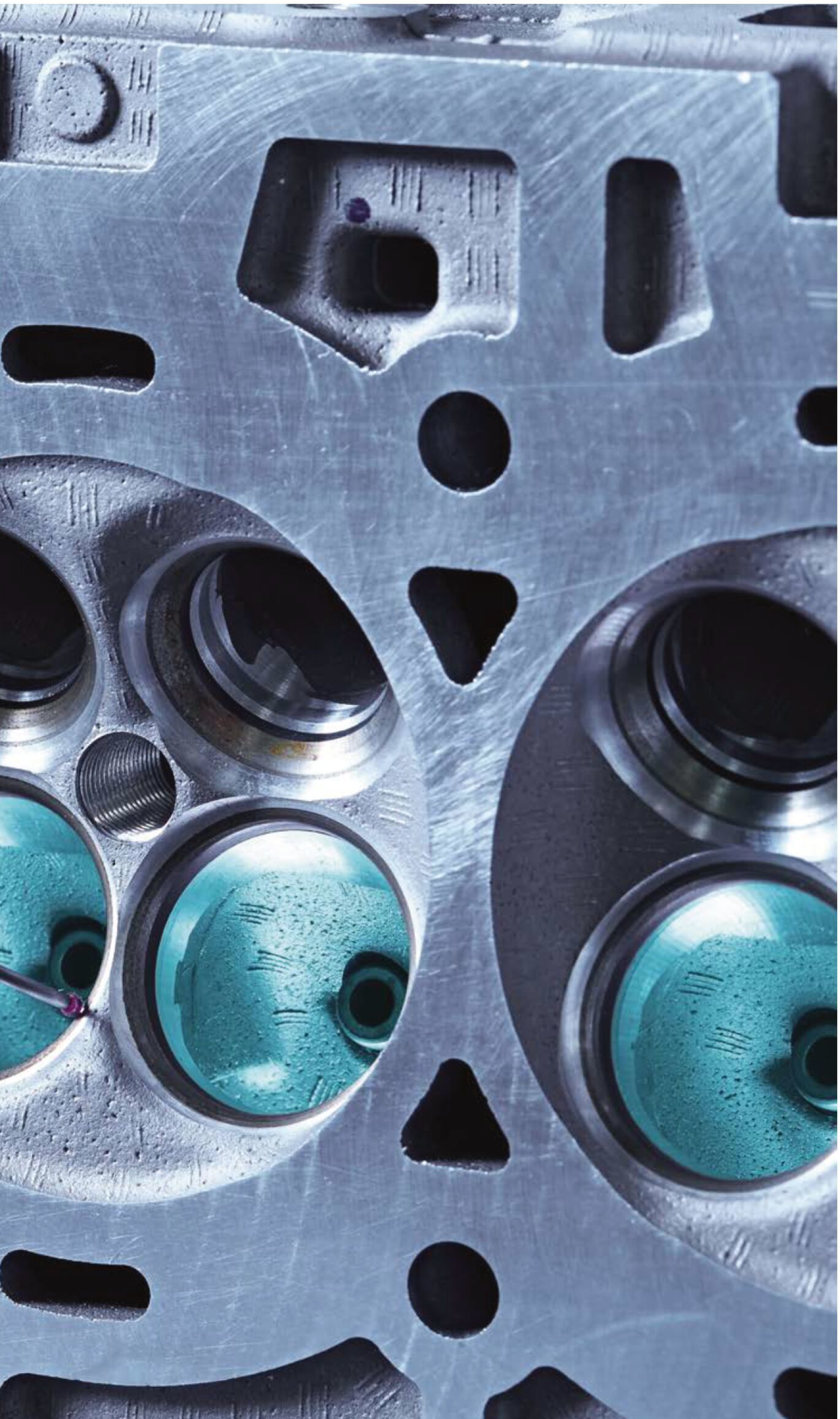
With five-axis machining, a motorsport manufacturer is able to measure the dimensional accuracy of any feature of pretty much any part

Elsewhere in this magazine we look at the world of machining, and discover the growing importance of automation over human intervention. Fully autonomous manufacturing has now not only become a viable option, but is possibly the *best* option for hi-tech engineering companies, and this is mainly due to recent advances in coordinate measuring technology.

Coordinate measurement machines (CMM) inspect and measure the dimensional accuracy of parts. They become an integral stage in the manufacturing process. Capable of capturing 4000 data points per second, every feature, surface or shape can be measured to within microns to ensure a part is within tolerance. At present, CMMs are predominantly used as part of the quality control stage of the process, once a part has been manufactured.

Flexible fixturing strategies are used to secure the part to the bed of the CMM machine in a particular orientation. The machine automatically picks up the required probe and hovers a few microns above the bed, using air bearings to smoothly travel along the machine's *x*, *y* and *z* axes towards the part.

Software is used to conduct 'off surface motion planning', which is effectively where algorithms determine the most efficient machine path from one measurement point to another without colliding with the part being measured, and this is calculated for all the axes. Thereafter, the probe follows this predetermined path and begins measuring.



There are several ways in which probes collect dimensional data with touch trigger and scanning the most commonly used methods. Touch trigger is essentially where discrete points are measured at defined locations and, when the stylus of the probe makes contact with the surface, a trigger event is generated. Within the body of the probe there are three rods or rollers that each rest on two balls, providing six points of kinematic contact. A spring is used to hold the stylus assembly against these contacts and re-seats the probe after any deflection.

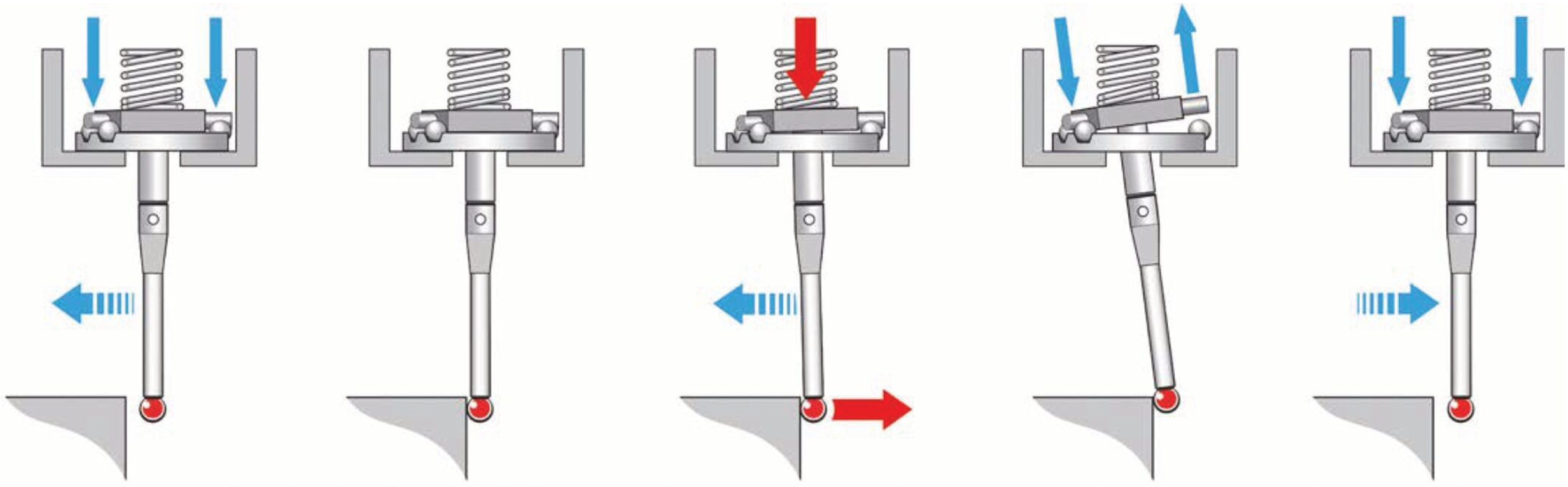
When the tip of the stylus has contacted the surface, the consequent contact force is resisted by the reactive force of the spring arrangement in the probe's head. This deflects the stylus, which pivots about the kinematic contacts, resulting in one or two of the contacts moving apart. The deflection of the stylus and the resulting trigger event is then detected and the machine's position latched electronically. The machine then moves away from the surface, allowing the stylus to re-seat back into its original location to within one micron, before beginning the next measurement.

Trigger happy

'To generate a trigger, the trigger force needs to be overcome as the stylus touches the workpiece,' says Andy Holding, marketing manager of CMM products at Renishaw. 'If I were to blow on the stylus, it would move to a certain extent, maybe nanometers, but that isn't a trigger. There can be vibrations and movement within the machine caused by accelerations and you want to minimise this to avoid any false triggering. The machine is a very lightweight structure, so you don't want to introduce any dynamic errors, which is why we use air bearings to ensure a smooth drive as it moves the probe around the part.'

To capture accurate profile and shape data, a large number of points need to be measured, which would take too long for a touch trigger probe. This is where scanning probes come

» Coordinate measurement machines inspect and measure the dimensional accuracy of a part and have become an integral stage in the manufacturing process



As the stylus contacts the surface, the spring, roller and ball mechanism within the head of the probe allows it to pivot, generating a trigger force, which is then translated into data

into play as they can quickly acquire a constant stream of data points as the stylus continuously travels over the part's surface.

There are several different principles by which these scanning probes function. The REVO RSP2 scanning probe uses a process of 'tip sensing' where a beam of laser light is directed from its source in the probe body, down a hollow stylus holder to a reflector at the tip and transduces the lateral displacement of the tip. Unlike conventional stylus holders that need to be as stiff as possible, the REVO stylus holder is designed to bend. This deflects the return path of the laser beam, which is received by a position sensing detector (PSD) also mounted in the probe body. Movement of the laser spot on the PSD is translated into a measurement output by combining it with the head and probe geometry and each of the CMM axis scale outputs. Thus, the exact stylus tip position in space can be derived. This all takes place while the stylus tip is dynamically scanning the part as the head moves synchronously with the CMM. High-speed sampling results in data capture rates of up to 4000 points per second.

> **» Both touch trigger and scanning probes require a vast array of stylus shapes and sizes to allow use on every type of profile**

Micron machines

Both touch trigger and scanning probes require a vast array of stylus shapes and sizes to allow use on every type of profile and feature. The stylus is the part of the system that makes contact with the component and consists of the stem and the styli tip. The most frequently used stylus is the straight styli, which can have stems made from titanium, ceramic or carbon fibre. These come in a variety of lengths, up to 800mm long for some applications.

The optimum stylus ball can be made from ruby, ceramic or tungsten carbide, although ruby is the industry standard. Synthetic ruby is 99 per cent pure aluminium oxide, which is grown into crystals at 2000degC and is one of the hardest known materials on earth. Consequently, it is extremely resistant to wear and so maintains accurate measurements.

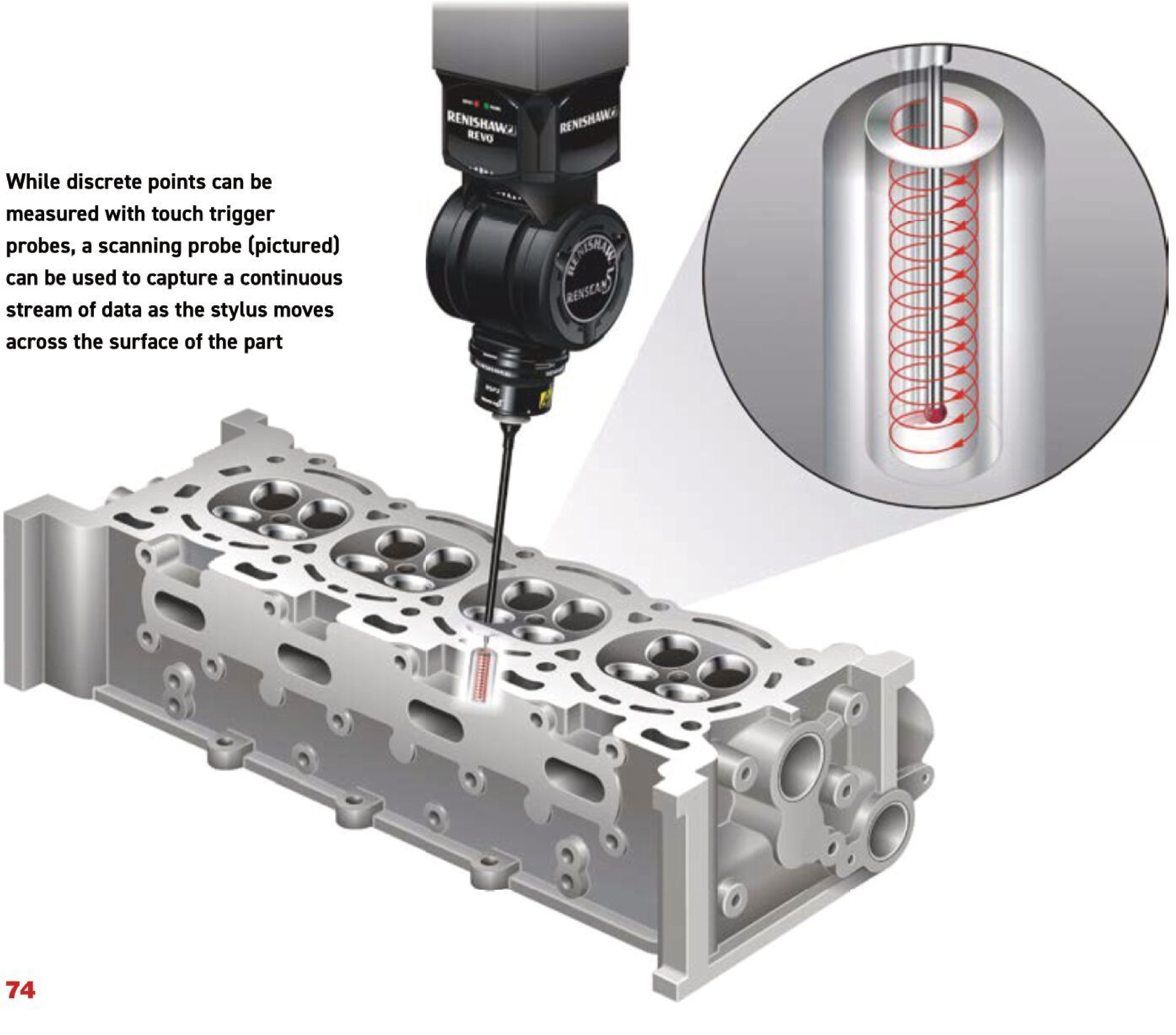
Also commonly used, particularly for indexing heads, is the multi-tip star styli, which allows holes to be measured and has the capability to contact features in many orientations, without the need to change the stylus. However, the most important aspect for the design of the stylus is to try and utilise the smallest styli with the shortest stem and fewest number of joints, to minimise mass and any consequent inertial errors.

Articulated heads

To carry out all the desired measurements of a part, the probe has to be able to move in different axes. Traditionally, CMMs have only had the capability to move in the x, y and z axes with the option of a rotary table. But recent innovations in articulating heads, such as the REVO technology developed by Renishaw, mean they now also have the ability to move in two rotary axes whilst measuring. This allows the CMM to conduct five-axis motion around complex parts with the machine moving smoothly, at constant velocities wherever possible, to minimise dynamic errors.

'In three-axis CMMs, the accelerations associated with moving the machine in discrete directions can cause inertial errors within the machine,' explains Holding. 'In five-axis CMMs, our controllers move the machine as little as possible while the head does as much of the work as possible. The head is also lighter, so it can move more dynamically and therefore minimise the machine distortion, which can detract value from the data.

'Our REVO system achieves infinite position capability, which also means you can get away with far fewer styli and stylus combinations,' adds Holding. 'Normally, with a fixed head,

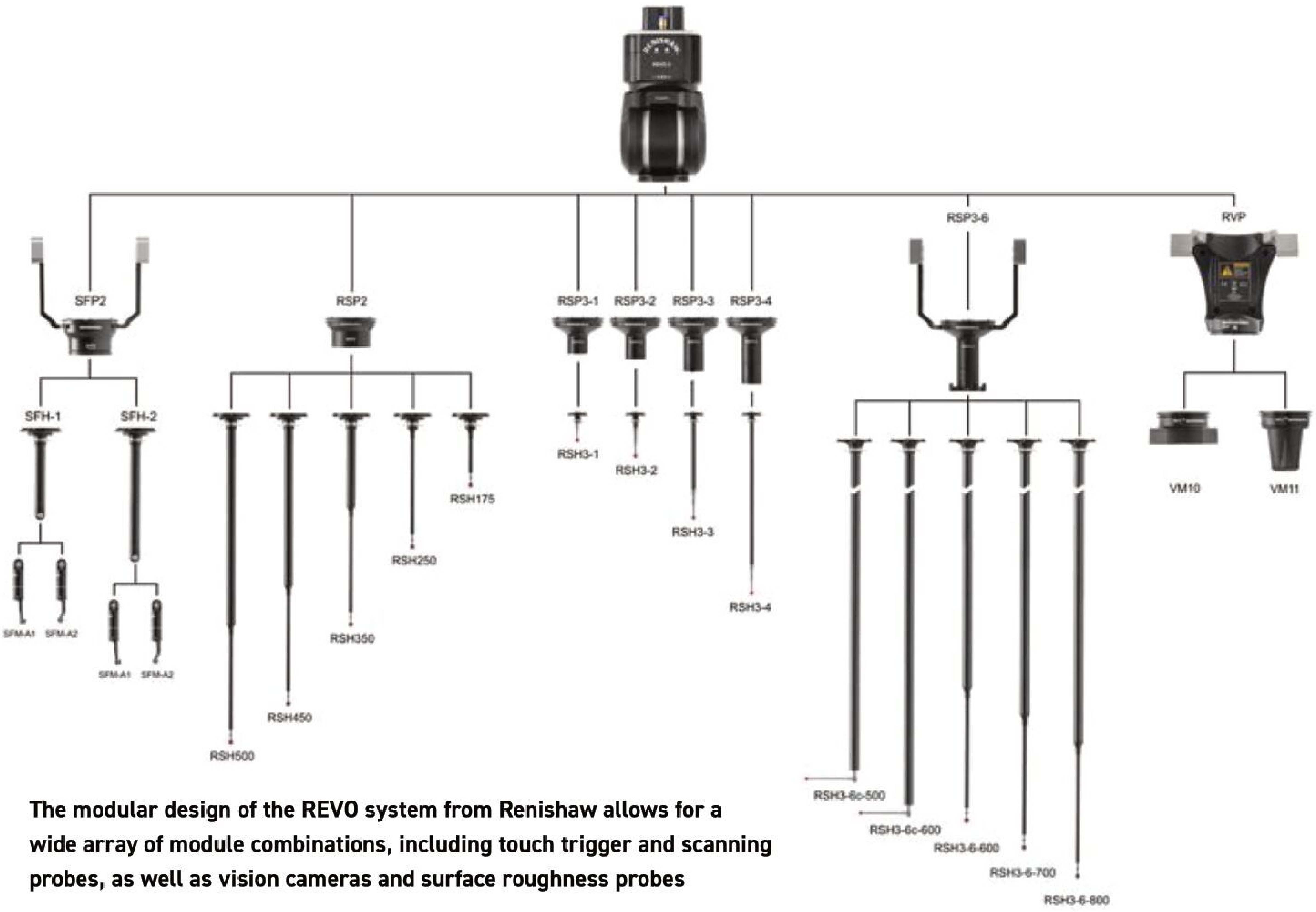


While discrete points can be measured with touch trigger probes, a scanning probe (pictured) can be used to capture a continuous stream of data as the stylus moves across the surface of the part

» ‘People often see surface roughness measurement as a black art, but really that’s because it’s mostly done in a very uncontrolled way’


The SFP2 consists of a two micron radius diamond tip that deflects vertically as it’s dragged across the surface of the component, going across the grain of the machining, thereby generating the signal in a similar way to a record player


A five-axis CMM using REVO. The CMM head automatically selects a stylus from the rack via magnets in the probe’s head



The modular design of the REVO system from Renishaw allows for a wide array of module combinations, including touch trigger and scanning probes, as well as vision cameras and surface roughness probes

you have to build many different stylus configurations, which then require storage. But then when you change the part, you may need even more different combinations. This can all be avoided with REVO.’

The key to REVO’s success is its modular design, which allows different probes and styli to be used all on one head. This is achieved through an arrangement of magnetic joints, which not only allows the machine to automatically pick up the required module (probe and stylus) when required, but also ensures the module is seated in the correct position immediately, ready to measure.

Roughness report

As well as its full array of touch trigger and scanning modules, another Renishaw system is the innovative SFP2, which is used for measuring surface roughness.

‘We use a two micron radius diamond tip at the end of a stylus, which is held in place by a spring-loaded joint, isolating it from any machine movements,’ explains Holding. ‘We apply the stylus to the surface at 90 degrees and the spring joint allows the stylus to move up and down as we drag it across the workpiece. Normally we do 10mm strokes, going across the grain or the direction of machining, in a similar way to a record player.’

This vertical motion is then translated into a roughness report via Renishaw’s bespoke scale and read head system. Previously, surface roughness measurement was done manually with a hand-held device placed on the surface, and a motor would drive the stylus across the workpiece. However, different operators can get different answers and the tools are extremely fragile. Some machine shops can spend tens of thousands of pounds on their surface roughness measurement capabilities alone.

Surface finish

‘People often see surface roughness measurement as a black art, but really that’s because it’s mostly done in a very uncontrolled way,’ says Holding. ‘Our SFP2 system offers huge benefits. Take a conventional three-axis CMM and a separate manual gauging station for surface finish monitoring. A particular part could take an hour and three quarters on the machine and 50 minutes on the gauging station, totalling two hours and 35 minutes. With REVO we reduce that down to one hour and 20 minutes because you can now completely remove the gauging station and use our SFP2 probe instead.

‘This not only reduces the footprint and cost, but also risk, because every time you move a part you risk damaging it, whereas with REVO all the measuring is done in one place.’

Renishaw's SFP2 probe measures surface roughness in a controlled manner, allowing for greater certainty in production

Styli come in many forms. The stems are often made from carbon fibre, tips are ruby balls, ceramic or tungsten carbide

» Probes have now been incorporated into the machining environment so the dimensional accuracy of a part can be monitored while it's being made

Five-axis CMMs, along with the advanced capabilities of Renishaw's REVO system, are allowing components such as engine blocks and cylinder heads to reach new levels of accuracy and certainty. The only issue is that CMMs are mostly used once the part has been made so, if there are any errors, production usually has to stop until the problem is solved.

So why not integrate the technology from CMMs into other machines and make inspection an integral part of the manufacturing process? Good news – they have. Probes have now been incorporated into the machining environment so the dimensional accuracy of a part can be monitored while it's being made.

In-process inspection

'From a machine standpoint, we absolutely love probes,' says Mark Terryberry, applications engineer at Haas CNC. 'We use probes for automatically setting up parts and tools and also for in-process inspection. When you use probes with machining, it creates an internal feedback loop throughout the process, rather than just a final inspection that is carried out offline. The machine can then make adjustments based on those in-process measurements.

'I help customers programme their machines and their first question is always about probing,' Terryberry adds. 'If a feature is made too small, they want the probe to quantify it, the tool to adjust automatically and re-run the part. If a feature is oversized, then they want to automatically machine a slave feature to ensure an inaccurate part is never mistaken for a correct part when coming off the machine. All of this logic is programmed into the Haas control.

'Ten years ago in-process inspection was not very common, but now it's a necessity.'

Calibration probes

In addition to part set up and monitoring tool wear, probes are also critical for calibration. Both machine tools and the working space are now standardised with various calibration probes such as the Renishaw ballbar, but the probes themselves also need to be calibrated.

'We have developed a Visual Programming System (VPS) where with a few button presses we can not only automatically calibrate the probe, but also use the probe to automatically find the centre of rotation on our rotary devices,' explains Terryberry. 'Machining five sides of a part within one operation is becoming increasingly popular, but to do that you have to be able to find the centre of the part quickly. So we've written probing routines, which just require a few answers to some questions. It's never been easier to probe.'

In addition to parts being inspected post manufacture, they can also be measured in situ, immediately after manufacture has finished. One of the best ways of doing this is to use the Equator Gauge from Renishaw, which measures and compares the dimensions of

» 'With a few button presses we can automatically calibrate the probe'

The Equator Gauge can be integrated into the manufacturing process and used to check parts as soon as they have been made. Robots move parts from the machine and automatically load them on to the Equator

Non-contact vision probes can also be used on five-axis coordinate measurement machines, allowing the measurement of 0.5mm diameter holes, for example. A 1.3 megapixel global shutter CMOS sensor and digital signal processor are used and the grey-scales of the images translate into spatial data

a manufactured part against another known 'master' part. The Equator Gauge can be used as a standalone quick check or can be fully integrated into a machining station. In the latter case, a robot picks up the finished part from the machine and secures it onto a platform, ready for the Equator to begin running through its measurement program. Therefore, not only has the part been machined automatically, whilst also being inspected, but it is then checked in more detail by the Equator, completely autonomously without any human intervention.

Master parts

'We supply machine shops all over the world,' Holding says, 'which means they could be making parts in temperatures between 10 and 50degC. Comparing the produced part to a drawing that was nominally correct at 20degC is unrepresentative, because the dimensions will vary with temperature. Therefore, a master part is produced and inspected on a CMM first, before being situated in the same working environment as the machine tools. Any temperature fluctuations in the environment are removed by re-measuring the master part, which has been subject to the same effects of the environment, but is of known dimensions

'This act of re-mastering the gauge re-zeros the system and can be conducted as frequently as the daily factory temperature profile demands. Moreover, any residual errors in the measurement of the part can indicate tool wear or drift over time. These errors can be corrected through automatically sending tool offset feedback to the machine tool controller, based on an average of part measurements.

'Rather than measuring every feature, only key features that relate to a particular cutting tool need be measured. This ensures parts remain within tolerance and confidence in the process remaining consisten can be gained.'

In addition to probes measuring real 3D parts that have just been manufactured, probing technology can also be used to work backwards – reverse engineering parts for further machining. 'We can use probes for adaptive machining,' explains Alan Mucklow, managing director of UK sales at Yamazaki Mazak. 'Take the example of an aerofoil that requires some detailed machining. Although the aerofoil service will have some tolerance, it may not necessarily be fully defined. Adaptive machining can measure the surface with the probe, generate a solid model, create a bespoke programme and output that to the machine, which can then conduct the cutting process. It's a fully automated closed loop system.'

Measure by measure

The racing industry has fully embraced the capabilities of both autonomous machining and autonomous measurement. Although both have obvious benefits for mass production, the ability of five-axis CMMs to measure any feature or surface, inside and out, at any angle or orientation, also brings huge advantages to complex motorsport components produced at lower volumes.

Witnessing the latest CMMs in action at Renishaw's UK base is incredible. These huge CMMs skate across the measurement area, release one probe and carefully select another, effortlessly gliding back to the part, where the head begins its controlled measurement dance, emitting a satisfying beep every time a measurement is taken.

Walking from the noisy machine shop to the CMM lab, you could believe you had gone deaf, because these machines operate in silence due to the low-friction design of the machine drives. Add to that the isolation of movement between the machine and probe head and you feel like you've accidentally ended up in the future.

Coordinate curing

Manufacturing and motorsport are not the only industries that benefit from the positional accuracy of advanced coordinate measuring systems. The medical world utilises such technology to help with illnesses such as epilepsy and Parkinson's.

Renishaw makes robots used for neuro-surgery, which help to deliver probes and drugs to precise locations in the brain. MRI data is used to develop a 3D image of the human body and the software controls a robot that tells the surgeon the exact position in which they need to drill into the skull to access the required part of the brain. The patient is often awake at the time and told to sing nursery rhymes because the surgeon needs a response. If they stop singing, the surgeon knows they have gone too far, and so backs out.

This process can also be used when patients are undergoing a seizure, so the surgeon can see where the active part of the brain is to precisely deliver the drugs.


Racecar engineering
Glickenhaus 004
Le Mans triple crown
Toyota's TS050 seals outright win again
Romeo C39

Shock developments

The damper's task in a coilover suspension is to control the behaviour of the spring, which ensures the tyres are in contact with the track surface as much as possible

» 'The main challenge is to fit all the required features of a high-performance damper into a very limited space'

Optimising dampers for different motorsport disciplines is a key facet of shock absorber technology. *Racecar* spoke to those at the forefront of suspension system development to find out more

By Gemma Hatton

Quite often, the only time we hear Formula 1 teams talk about suspension is when they are arguing the legality of their clever designs with the FIA and the rest of the paddock in the latest regulation row. So why can't teams leave their suspensions alone? In short, because suspension is arguably the most important tool for gaining track performance.

The main purpose of the suspension is to absorb the oscillations between the vehicle body and the wheel, generated by undulations in the track surface. Also, maximum contact between the tyres and the track is needed for the most time to achieve optimum grip. Suspension also plays a role in maximising cornering stability, braking distances and acceleration. So you can see why motorsport engineers invest so much time, resources and money into manipulating suspension characteristics in their continued quest for that optimum set-up. And much of the work is centred specifically on dampers.

'The main damping concept of flow architecture, and how the pressure is built up in the damper, is the same for all our dampers in high-level motorsport,' says Claes Hesling, project manager, racing, at Öhlins. 'Our damping technology ensures that the damper responds properly under all conditions without experiencing cavitation. This helps minimise the variation in contact patch load, which in turn optimises grip and control.

'Another aspect is the versatility, which is achieved with flexible valving systems to ensure powerful and precise adjusters.

'Of course, the main differences between the dampers for different motorsport categories is the size and weight demands,' Hesling adds. 'In all forms of motorsport you want to achieve the lightest and most efficient packaging possible, but it cannot be at the expense of durability. A damper failure would be catastrophic, so you try to be as close to the limit as possible without going over it.'

Formula 1 dampers

In Formula 1, suspension design is extremely aero driven because the main source of grip comes from the downforce generated by the aerodynamic package, as opposed to pure mechanical grip. Therefore, F1 engineers are continuously hunting for ways to use suspension behaviour to influence ride height and other parameters to increase downforce.

Of course, these types of active systems have been banned since the 1990s, with current regulations dictating the only method in which suspension design can result in an aerodynamic gain is when it is 'wholly incidental' to the primary purpose of the suspension itself. Not that this stops teams trying, as past experience has proven. Collapsible heave systems have been used at the rear to reduce ride height, with teams optimising front suspensions to increase ride height at the end of straights, as well as altering pushrods and uprights to lower front ride height at the corner apex.

Geometry set

It is not only the behaviour of the suspension that is aero driven, but also the geometry. For example, in Formula 1 the lower front wishbones are in line with the axle because this ensures they do not disrupt the airflow coming off the front wing, minimising any potential turbulence and consequent drag. This may not be the most mechanically effective design, but the desires of the mechanical engineers are some way down the pecking order in F1.

'The main target of the dampers, or shock absorbers, in Formula 1 is to control the aerodynamic platform of the car because this is where you get the most gain in grip,' confirms Olivier Lardon, manager of motorsport dampers at ZF Race Engineering. 'However, the suspension is also linked to the tyres, so you can also use dampers to adjust tyre temperature and therefore bring the tyres into the best working range to achieve optimum grip. For example, if you have larger or stiffer tyres, you may need to increase your damping coefficient to get more energy into the tyre.'

» The main target of the dampers, or shock absorbers, in Formula 1 is to control the aerodynamic platform of the car

Tyre role

The characteristics of rubber ensure tyres naturally contribute to the damping of the unsprung mass and must therefore not be forgotten. This behaviour can be utilised by the suspension set-up to try and control bulk tyre temperatures and grip. At high speed, the high-frequency inputs of the track help generate that bulk tyre temperature, so modifying the high-speed damper settings will have minimal effect on tyre temperature, but may compromise other areas of handling.

However, at low speeds, particularly for stiffer tyres such as those running in colder ambient temperatures, the compression or bump of the damper is increased. This higher damping generates more resistance, which transfers additional energy into the tyre as the 'damping' part of the tyre is being utilised rather than the 'spring' part of the tyre.

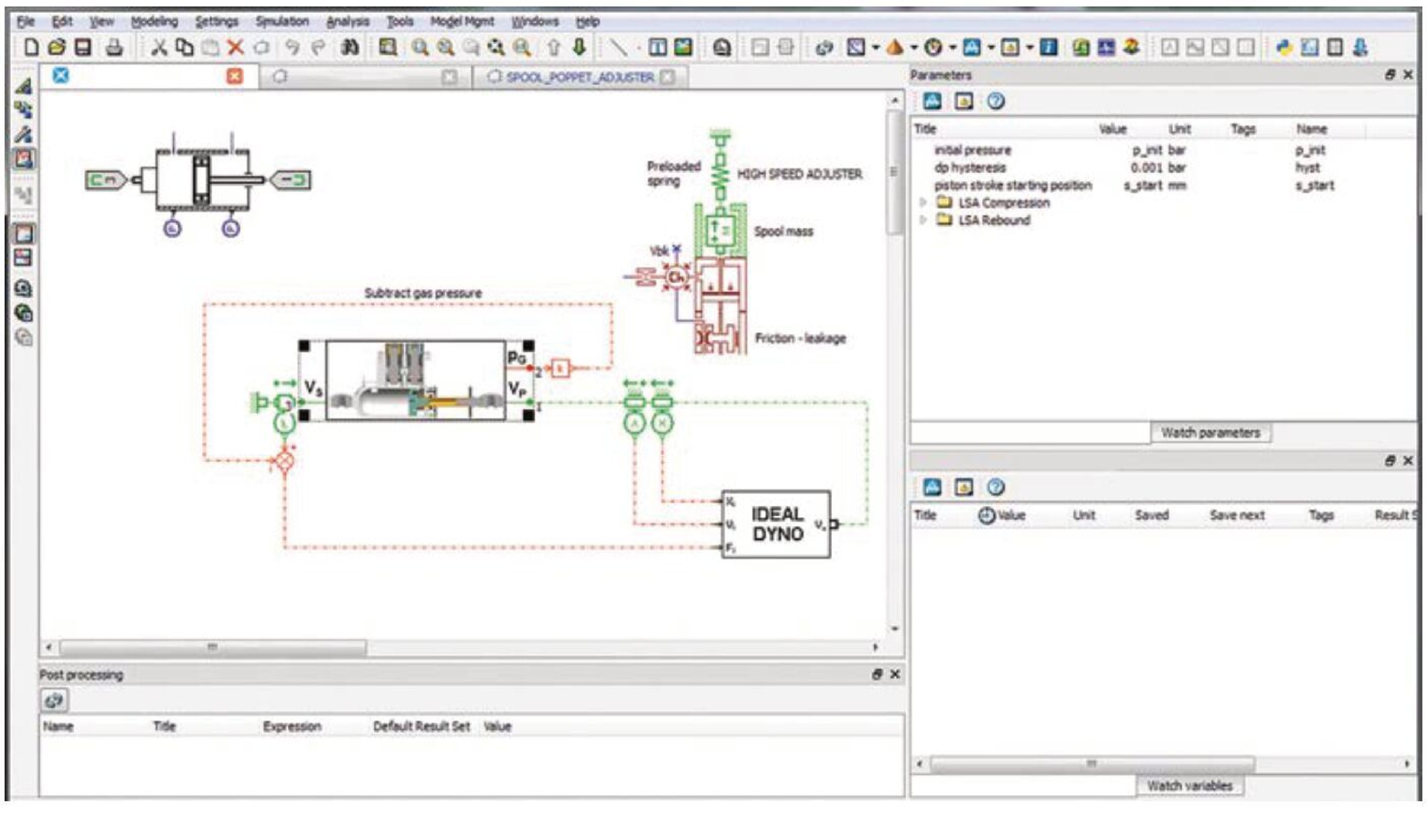
On the other hand, if you are using softer compounds that are more susceptible to overheating, low-speed compression should be reduced to achieve a more benign pattern of behaviour. Interestingly, in the motorbike world, a stiffer suspension actually decreases tyre temperatures.

'In Formula 1, weight and packaging are crucial, which pushes us to use extreme materials such as composites, magnesium and titanium to achieve the weight targets,' says Hesling, 'The main challenge is to fit all the required features of a high-performance damper into a very limited space.'

Things are a bit different in Formula E. The word 'Formula' may lead you to think that these electric racecars face the same suspension challenges as Formula 1. However, due to the

Each motorsport discipline experiences different loads at the wheels, which require contrasting damping characteristics. This leads to a wide array of design solutions, as shown here. Top is a ZF Formula 1 damper, lower left an Öhlins Formula E version and on the right a ZF Rally damper (not to scale)

Models are built to help engineers simulate, and therefore define, the optimum characteristics of their damper design



Parameters

Title	Value	Unit	Tags	Name
initial pressure	p_init	bar		p_init
dp hysteresis	0.001	bar		hyst
piston stroke starting position	s_start	mm		s_start
LSA Compression				
LSA Rebound				

Title	Value	Unit	Saved	Save next	Tags	Result S

Name	Title	Expression	Default Result Set	Value

» Formula 1 cars drive on racetracks, whereas Formula E cars race in cities and so there are more inputs from the bumpy track

very nature of the inner city circuits and the strict regulations, there is much less emphasis on aerodynamic grip. That said, the tracks are bumpy, with many kerbs, and the tyres have less damping due to their thinner profiles, so improving mechanical grip is a more important consideration for Formula E cars.

'Every category presents different challenges, and our job is to optimise our suspension products around these issues,' says Heinz-Joachim Gilsdorf, senior manager motorsports chassis at ZF Race Engineering. 'For example, Formula E is not as fast as Formula 1, therefore you don't have such complex aerodynamic packages, which result in lower levels of downforce and reduces the consequent loads on the suspension. On the other hand, Formula 1 cars drive on racetracks, whereas Formula E cars race in cities and so there are more inputs from the bumpy track.'

Extreme bump

The extreme of 'bumpy' is, of course, rallying, where maintaining mechanical grip, regardless of whether it's on a mud, snow, ice or gravel stage, is the number one priority.

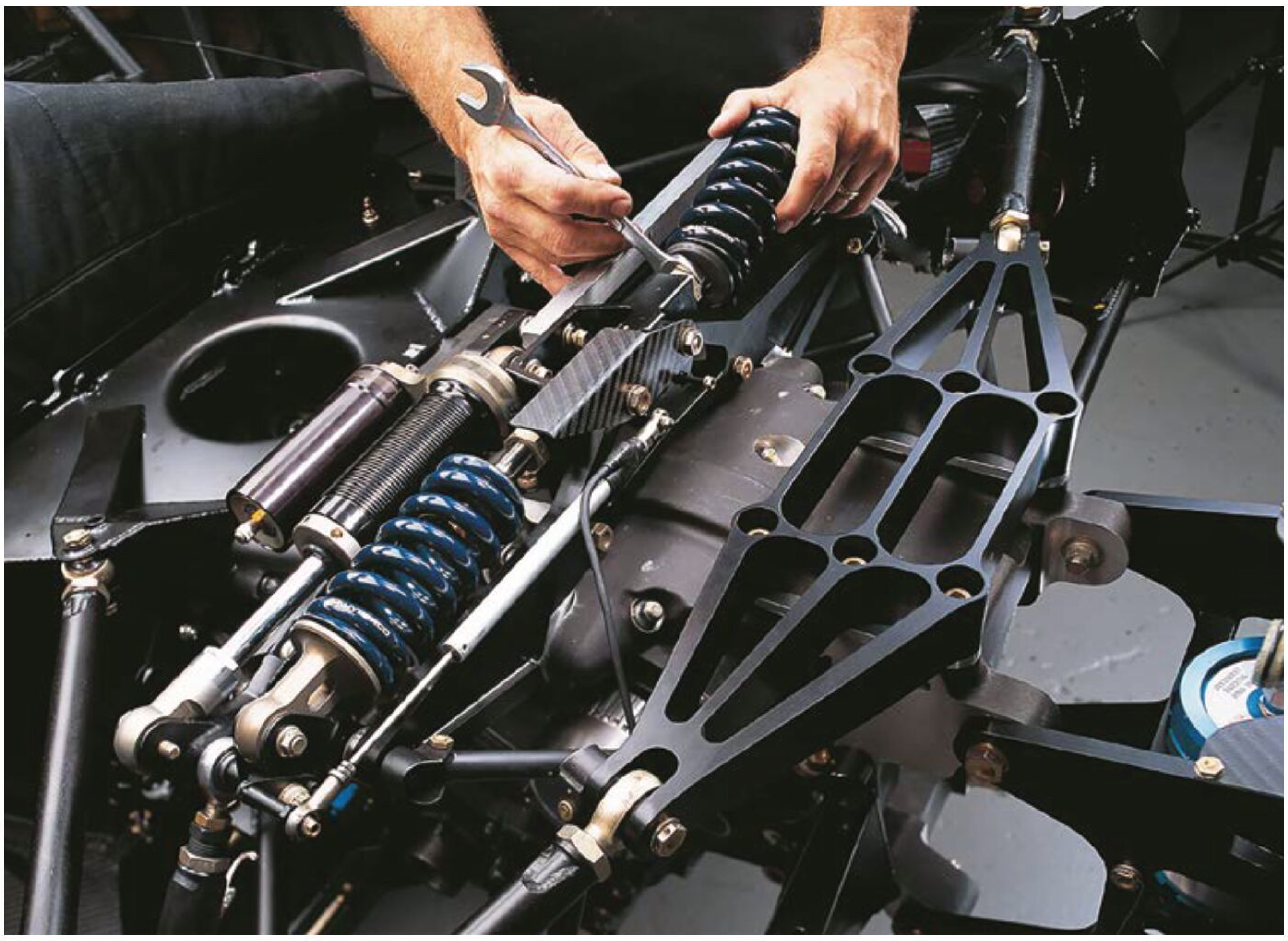
'On gravel and tarmac rallies, initial damping is relatively soft on both the bump and rebound side to try and get the car to float along the track,' explains Lutz Passon, head of the motorsport department at KW Automotive. 'However, during high-peak loads, you have to increase high-speed bump and rebound forces to control the body motion of the car.'

These bigger loads require much larger dampers, with some measuring strokes of 300mm in WRC, compared to 40mm strokes in Formula E. With the FIA regulations dictating rally cars feature MacPherson strut suspension front and rear, the side forces are much higher than a Formula car. This demands an overall stiffer damper with larger piston rods (or cartridge), which can measure up to 45mm in diameter. Whereas Formula E has double wishbone suspension, which results in minimal side forces so smaller piston rod diameters of only 8mm can be used.

'A rally damper is exposed to extreme conditions and load cases, and therefore the challenge is to design a damper that


The five-way damper from KW Automotive


F1 dampers are used by competing teams to influence aerodynamic performance and also to control tyre temperatures


Race engineers adjust dampers by clicks, altering the valving within them in stages to increase or decrease the resistance

PEGASUS

Stocking distributor of
silicone hoses

Most comprehensive stock
(and most helpful sales staff) of
AiM automotive data acquisition
products in the USA

Distributor of genuine
Red Head push-pull
refueling valves

US importer of
Jabroc® skid plate sheets

Stocking distributor of
MS21071 Apex Joints
(all sizes, ¼" to 1 ¼")

... and much more!

Pegasus Auto Racing Supplies • New Berlin, WI USA
800-688-6946 • 262-317-1234
PegasusAutoRacing.com
Racers serving racers around the world since 1980

motorsports quality
ROD ENDS, SPHERICAL BEARINGS
and BUSHINGS

contacts in English, Deutsch, Français, Italiano

AURORA®
RODOBAL®
inch - metric
ORIGINAL PERMAGLIDE®
Seals-it®

ROD ENDS ACCESSORIES:
side seals, protection boots,
jam-nuts, right-hand and left-hand
grooved bearings staking tools

most extensive stock in Europe of US and EU made parts
basic / regular / top performance product lines,
flexible service, worldwide delivery
support service to OEMs and regional distributors

Getecno Ltd. - ITALY
info@getecno.com

Intelligent Fully Featured Battery Power Control Systems

POWERBOX
HP 8441
NEW

Cost Effective
Practical
Incredibly Versatile

Fully programmable
power control in a
user friendly package.

Future Upgrade Path
to *HP8440*.

Main Features:
- 180 Ampere continuous.
- 34 Output channels controlled as a function of conventional switches, CAN inputs or Virtual channels. With wiper Park on dedicated channels.
- Weight 496 gr.

MEMBRANE PANEL

CAN Controlled
Membrane Switch Panel.
Tactile Operator Feedback.
Multi Tap Capability.
Warning LED's.
Available With Your
Custom Design.

POWERBOX
HP 8440

Main Features:
- 200 Ampere continuous.
- Programmable Inrush Currents
- 34 Individually Programmable Output Channels
- 11 Conventional Switched Inputs
- 32 CAN Input Channels
- 20 Virtual Logic Channels
- CAN Export Facility
- Weight 680 gr.

Future Proof With
Firmware upgrades

OVER 1000 UNITS SOLD WITH PROVEN RELIABILITY
ENGINEERED & PRODUCED WITH OUR EXPERTISE IN HOUSE. LEARN MORE AT HPELEC.DK

HP ELECTRONIK
Lundvej 17-19, Lund
7400 Herning · Denmark
Tel. + 45 9626 4333
Fax + 45 9626 4233
info@hpelec.dk
www.hpelec.dk

has superior end stop protection,' explains Hesling. 'Of course, this has to be achieved in combination with a subtle ride performance to avoid affecting the level of mechanical grip that is so crucial in rallying.'

Race engineers will often adjust the dampers by 'clicks' in low-speed and high-speed bump and rebound. These clicks essentially alter the valving within the damper, to increase or decrease the resistance and therefore the force in relation to the velocity of the piston rod. Some motorsport dampers can have up to five-way adjustment, so both bump and rebound can be adjusted at low and high speed, with the fifth way being the control of the high-speed blow-off valve.

GT3 special

KW Automotive has developed its new version of an adjustable four-way damper specifically for GT3 cars. The possible adjustments are in low-speed and high-speed bump and rebound

'Our design allows a higher flow rate through the valves, and also our valving is all located in the same place at the bottom of the damper, both of which ensure a good response, and this is the highlight of this design,' explains Tim Schroder, race suspension engineer at KW Automotive.

'We use a completely closed piston, which is a new concept for us. We really started the design of this solution with a blank sheet of paper. The closed piston allows larger flows through the valves, which lowers the pressure within the damper and ensures better hysteresis, all of which works together to greatly improve the damping response.'

Future iterations of this design could include an optional blow-off valve. This would be located on the piston, so that when the racecar hits a kerb on the track, these high-peak loads are absorbed quickly, without affecting the vertical movement of the vehicle body. 'We are also developing another type of valve that we call IDC, Intelligent Damping Control, because it will be able to define whether the input into the damper has come from the wheels or the vehicle body, and so will be able to react accordingly.'

Future shock

As for the future of damping technology, electronically-controlled damping remains out of reach for motorsport. The technology already exists, it's just the regulations do not allow it. These systems would enable full optimisation of the suspension and damping to improve the handling of the car through the entire spectrum of experienced loads. However, the complexity of these systems opens the doors for endless possibilities for both engineers and drivers to try and define. Hence why they are banned. So for now, it remains the engineers' job to control mechanical dampers with adjusters.

Spring time

High-performance springs are another crucial element of a suspension system. They have to be designed to ensure a consistent and accurate rate with every increment of deflection. This is achieved in two parts, says Mark Campbell, engineering manager at Hyperco: 'To design these precision springs, you have to understand the 'bowing and buckling' that results from four critical physical parameters, and their relationship to each other. These include total deflection to free length ratio, mean diameter of body coils to wire diameter, free length to end coil ID [inner diameter] and corrected stress level of the spring at solid height.'

Skilled operators

'You also have to be able to manufacture the springs accurately, which requires precision equipment with skilled operators,' Campbell adds. 'Production processes that additionally affect linearity of rate are the squareness and degree of the end coil grinds, centring the position of the end coils with respect to the centreline of the spring, end coil tip thickness with respect to wire diameter and end coil positioning from one end of the spring to the other.'

Forming process

Springs are manufactured using a forming operation, which is significantly different from traditional machining operations.

» Initially, the springs are coiled longer than the finished free length

'I relate forming operations to a quarterback throwing a football to where the receiver isn't when he releases the ball, and hoping they both arrive at the same place at the same time,' says Campbell.

Initially, springs are coiled longer than the finished free length. For example, a 14in, 250lb/in spring with an ID of 2.5in is often formed to 18-19in long when it comes off the coiler. It is then stress relieved and pressed, with the initial pressing operation proving critical as it puts the 'memory' into the spring.

'Pressing the spring brings the free length down to around 14.75-15in,' explains Campbell. 'The spring is then ground on the ends. After that, it goes to shot peening, with a follow up low-temperature stress-relief operation to seal in the residual compressive stresses imparted during shot peening.

'Both shot peening and low-temp' stress relief operations change the physical parameters of the spring slightly. The last pressing stage then locks in the final free length.

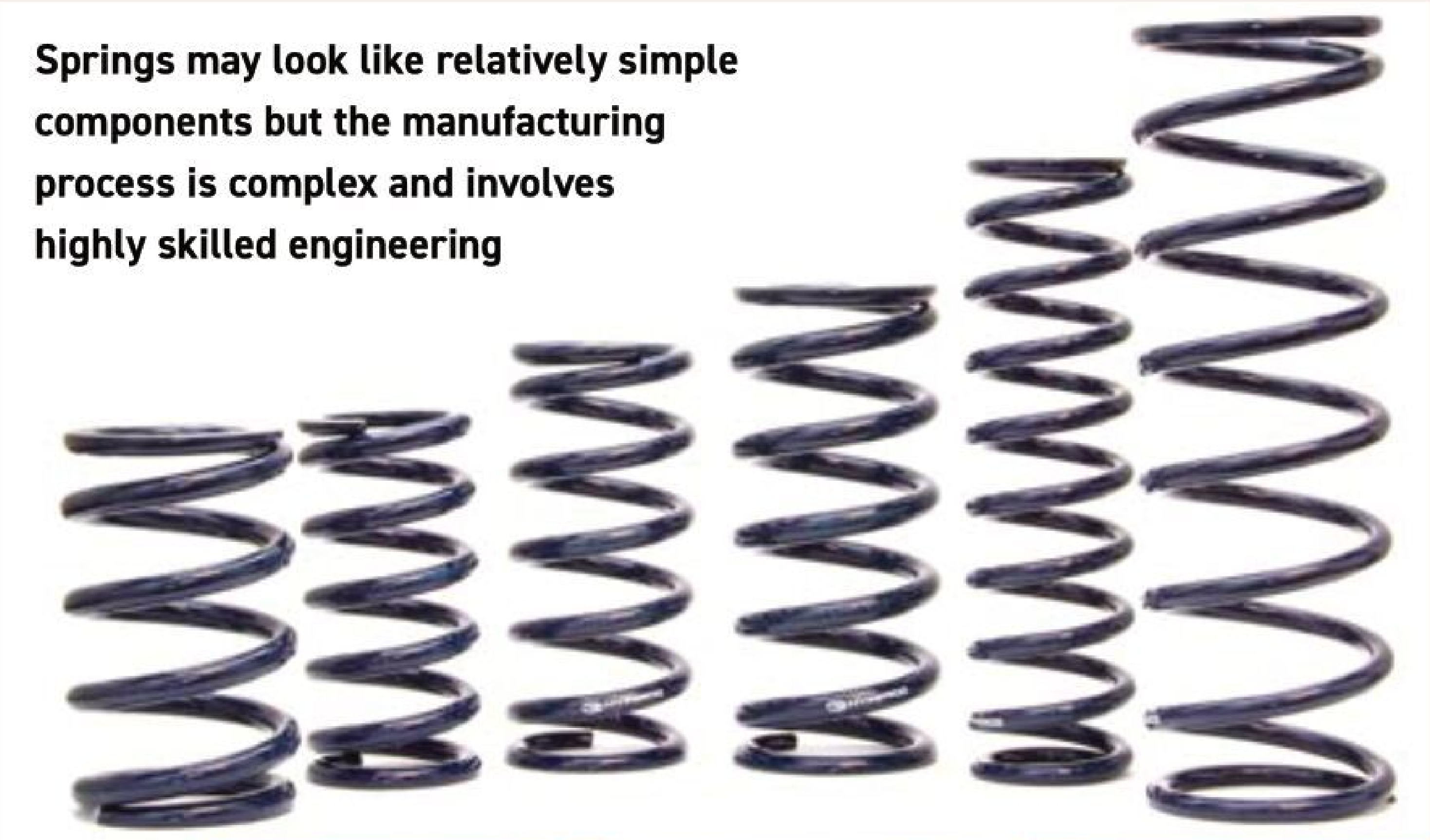
'All our coils must then pass a final inspection to ensure they are in compliance will all dynamic performance criteria.'

Spring perches

You may think that the spring perches on a coilover shock absorber are parallel, but they are not, as the perch on the body sits at a slight angle determined by the thread pitch used. This thread fitment between the spring perch and shock body can have a huge impact on the bowing of the spring during deflection, as well as adversely affecting the rate linearity.

'The number of threads per inch can also affect this,' continues Campbell. 'If a coarse pitch thread is used and the fitment of the threads is relatively loose, the shock body perch can tilt considerably and induce bowing into the spring. This is particularly problematic in classes where coilover adapter kits are used on a non-threaded shock to allow coilover operation. Many of these kits are very sloppy and create perceived spring bowing issues when the spring is not the problem. The problem is the shock body perch is tilted a few degrees because of the thread pitch.

'From our point of view, shocks using fine pitches with a tight class of tooth / groove engagement provide the best mounting to ensure accurate linearity of rate and best shock / spring assembly performance.'



Springs may look like relatively simple components but the manufacturing process is complex and involves highly skilled engineering

Spring perches on a coilover shock are not parallel, but sit at a slight angle

ÖHLINS
ADVANCED SUSPENSION TECHNOLOGY

Öhlins USA

7-Post Shake Rig

**4- Post packages also available*

Highlights of benefits of shake rig testing over track testing

- Testing available in all levels of Motorsports through Aftermart and OEM.
- Rig presentation is tailored to the knowledge and needs of each customer.
- More cost-effective
- Extremely repeatable
- No weather dependency
- No driver influence
- Productivity is also increased, more changes can be evaluated during the testing.

For more information:

Call or visit our dynamic group website @ ohlinsusa.com/vehicle-dynamics-group

OHLINSUSA.COM -800-336-9029

» Rig testing is not especially new, but in modern motorsport it is certainly extensive

Shake down

From K&C to seven-post, there's a wide range of test rigs now available for checking, testing and developing motorsport suspension systems. Here's *Racecar's* guide to all you need to know about these extraordinary machines

By JAHEE CAMPBELL-BRENNAN

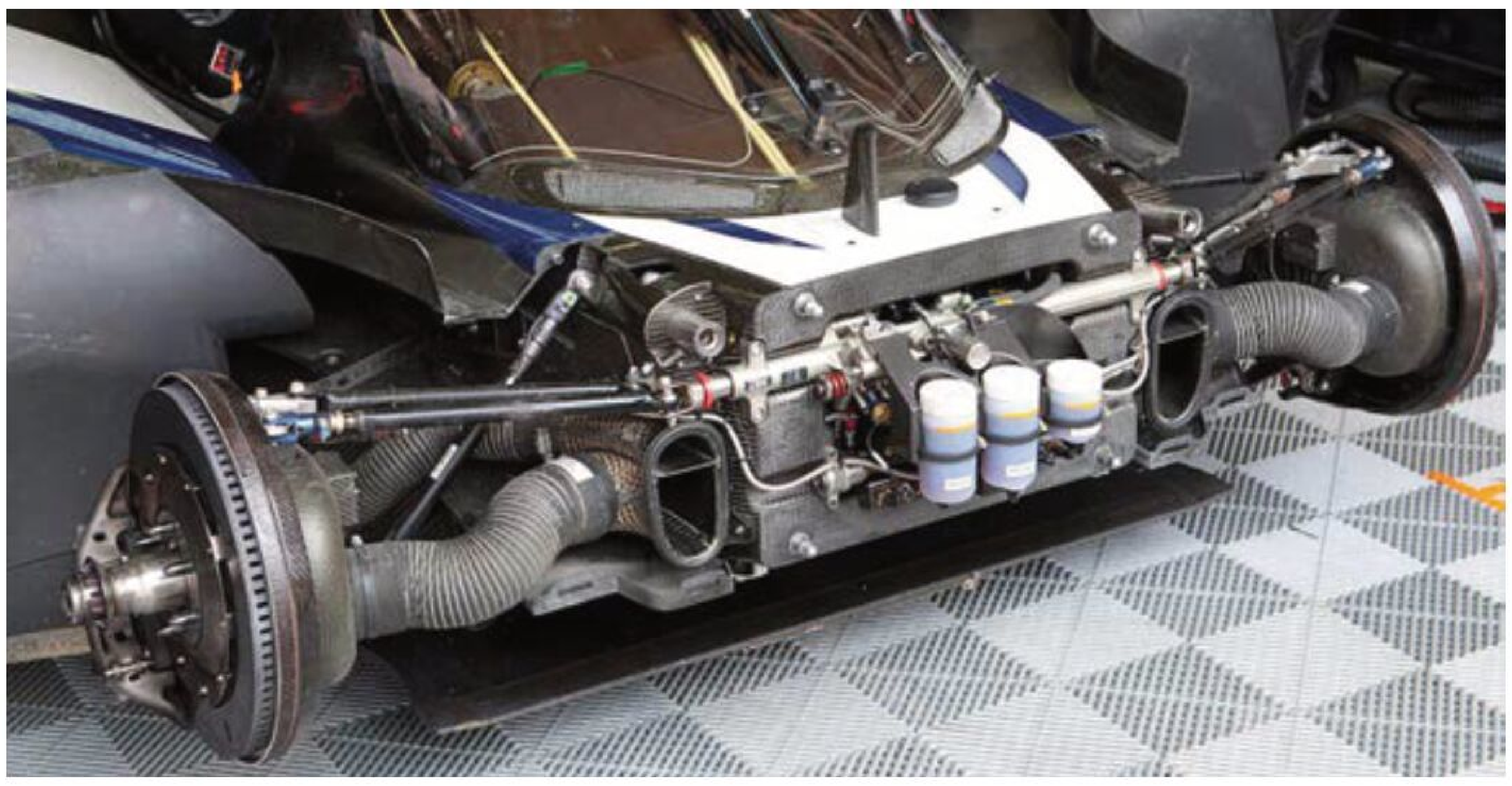
The role of a racecar's suspension is a complex one, and includes control of wheel orientation, deflection, how accelerations are transmitted into the vehicle body and also the effectiveness of the overall aerodynamic package.

Usually, open wheelers, prototypes and GT racers utilise a double wishbone arrangement, whereas saloon, touring and WRC-style cars often run a MacPherson strut at the front axle.

Compliance and flex

Double wishbone systems often have chassis mounted spring-damper units, which must include a linkage to enable their actuation. This additional structural member is known as a pushrod (loaded in compression in bump travel) or pull rod (loaded in tension in bump travel). The pushrod / pull rod actuates a component known as a bell crank, which pivots around a fulcrum to exert a force on the damper.

Toyota F1 car undergoing seven-post rig testing at TMG's facility in Cologne



The classic double wishbone suspension arrangement, shown here on a Peugeot LMP1 car

Peter J Fox

Large forces generated in cornering can cause suspension components to flex substantially

Ginetta Racing

Dimensional discrepancies might be introduced during a build (but that's not the case here!)

Running through the load path from the wheel upright to the damper in this inboard arrangement there is an array of bearings, fasteners and joints the force must journey through. These components help designers to tune the inherent compliance and flex of such a system and its influence on the kinematics.

Pushrods, in particular, are susceptible to bending modes, control arms and bell cranks deform, while fasteners and bearings introduce backlash and flex. MacPherson strut configurations, on the other hand, don't have pushrods or bell cranks as the spring-damper is mounted directly to the wheel upright. It does, however, mean the damper unit essentially acts as the upper wishbone and therefore must react to significant loads during cornering, introducing flex into the system.

Understanding the effects of flex and deflection, and their influence in a suspension system, is known as a compliance study.

Compliance is, essentially, understanding the geometric effects of the forces a suspension system is subjected to during accelerative loadings, and how these forces cause the suspension to deform and influence the orientation of the tyre's contact patch.

Kinematics

Kinematics characterises two degrees of freedom (DoF) – vertical translation and rotation around the steering axis. Compliance focusses on understanding the movement of the wheels in the remaining three DoF of which they are not intended to operate in – longitudinal translation, lateral translation and lateral rotation. Here we're considering rotation around the transverse axis separately, as it is not a function directly controlled by suspension. In short, kinematics is the study of intended wheel movement, while compliance is the study of unintended wheel movement.

Kinematic and compliant behaviour are studied through virtual assembly and simulations, and multi-body analysis software is used during the design phase. As ever with simulation, it is not accurate enough on its own to trust without verification. The mechanical properties of every link, member, fastener and part must be accurately understood and put into the software to simulate compliant behaviour, while relative movement and clearances in bearings and other hardware must be precisely modelled to understand the relative movement of components in kinematic simulations. Quite a task.

In fact, the hand-built nature of racecar parts can lead to tolerance stack ups and dimensional errors, which can result in the K&C (kinematic and compliance) behaviour of the suspension producing some unwanted effects. Therefore, teams need to assess the K&C qualities of their racecar in a controlled environment.

MIRA

MIRA's K&C rig can simulate the forces and loads placed on a vehicle's suspension system within a controlled and repeatable environment. Roll is being replicated here

» Monitoring relative wheel movement to generate the data are six DoF displacement sensors… mounted to the wheel centres

Horiba MIRA has a special K&C rig for exactly that. Clamping the chassis to a large, rigid bed plate and supporting the wheels with four pads, the car can be actuated in pitch, heave and roll modes to assess kinematic behaviour. Longitudinal, lateral and rotational forces can be put through the wheels to assess compliant behaviour, while steering and brakes can also be actuated by the rig control system to offer full and repeatable control of all dynamic situations a racecar may be exposed to.

The wheel pads can be moved with a lateral and longitudinal offset. This allows the wheel to be moved left / right or fore / aft of the wheel centre respectively. In this manner, a whole range of potential loading scenarios can be simulated. Tests in a controlled environment such as at Horiba MIRA are repeatable, but notably are also quasi-static, preventing frequency response related noise / variables from the data that would be experienced with measurements gathered from track running.

Rigged to win

Generally, a K&C rig is used by race teams in one of three different ways: to verify / correlate initial CAE (computer aided engineering) models before proceeding with further optimisation; to gather information in order to generate an initial model or – without CAE – to understand the characteristics of a previously unknown suspension system.

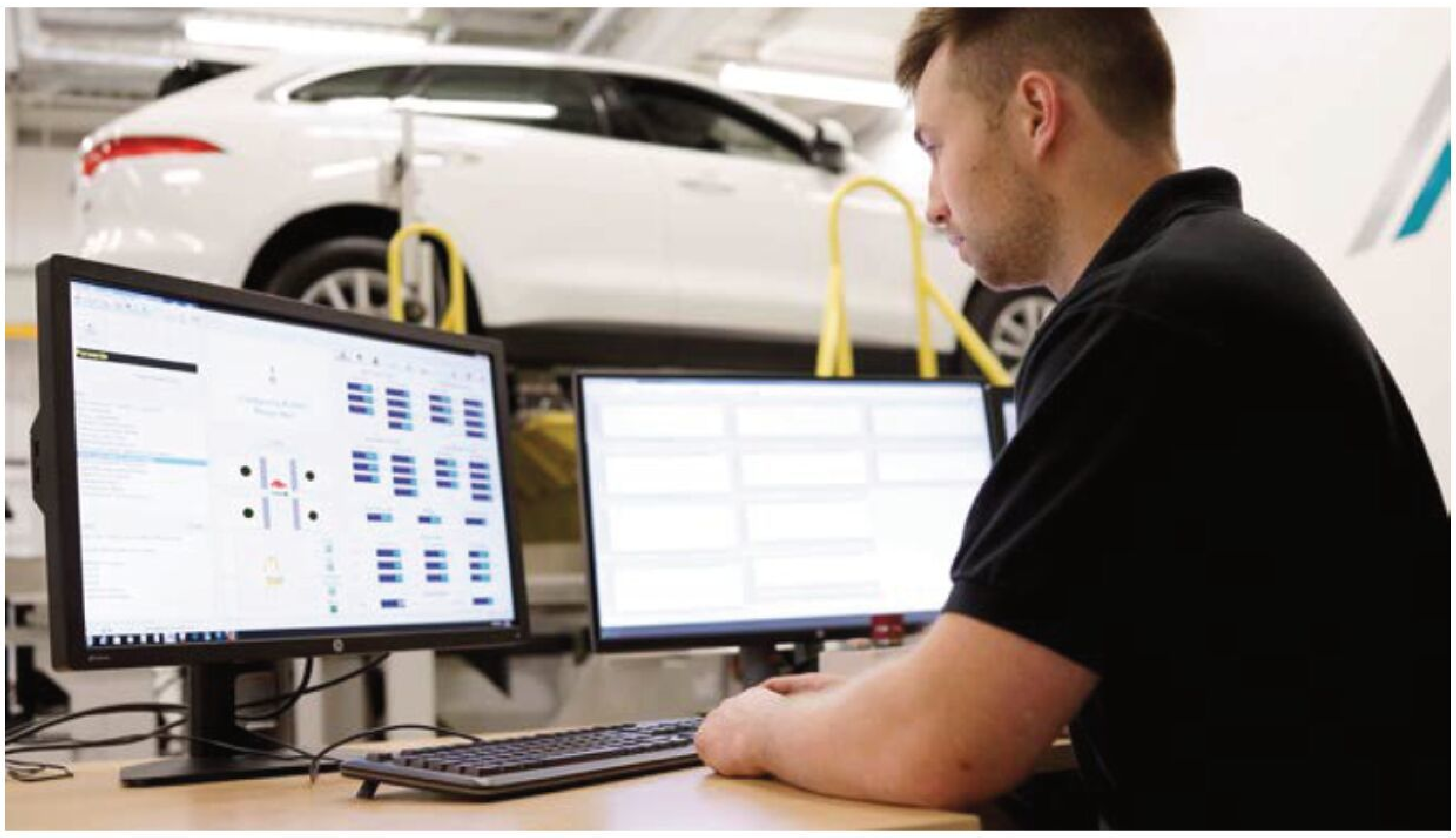
With kinematic assessment, a range of inputs can be applied to the chassis and wheels. Data for camber gain, bump steer and caster angle, to name just a few, is collected and fed back to the controller for analysis. Monitoring relative wheel movement to generate the data are six DoF displacement sensors (three degrees of translation and three degrees of rotation) mounted to the wheel centres.

'Differences and discrepancies from design intent usually present themselves through the assumptions made in the CAE model inputs,' says Luke Cosgrove, K&C facility team leader at Horiba MIRA. 'The model can only be as good as the boundary conditions that are provided, so we see common sources of error from play in joints, flex in the chassis and so on.

'Teams usually arrive here with results that they are expecting to see, so it is mostly a process of verifying those results.'

Gathering reliable information on how the vehicle performs with the tyre is especially important, because it has a significant influence on the suspension due to its own frequency response. Tyres are also particularly difficult to model due to their non-linear behaviour.

Suspension designers use various approaches to minimise and constrain



MIRA

Data from the K&C tests at MIRA can be monitored live by technicians, and also stored for later analysis

On the MIRA rig, the chassis is clamped to a large and rigid bed plate while the wheels are supported by four pads. The test car can then be actuated in pitch, heave and roll modes

unwanted DoF, yet no system can be infinitely stiff – the approach to understanding compliant behaviour of a system is slightly different.

Loads are exerted onto the chassis or the wheels and the resulting translational and rotational deflections are then monitored, allowing the engineers to understand questions such as how much does a wheel centre translate in the longitudinal axis during braking? And does this induce any toe angle?

'There is usually a suite of standard tests that we complete when teams arrive, but sometimes we also devise some unique tests to highlight specific areas when teams want to investigate something in particular,' notes Cosgrove. 'Similarly to kinematic assessment, the data gathered from the compliance rig is used to serve as either input into CAE models, or an exercise to gain initial understanding of the system if there isn't a model.'

Tub stiffness

Using an optical imaging system, the K&C rig has also found a use for this system in verifying stiffness CAE for carbon monocoques.

'Placing markers at specific points of the chassis has proven useful in evaluating flex in specific areas,' Cosgrove tells us. 'We use a camera imaging system to help highlight areas of localised compliant deflection, which has uses when we're looking to evaluate the rigidity of spherical bearing joints or chassis mounting areas, for example.'

When abnormal behaviour is found, a process of elimination is usually followed to diagnose the root cause. 'Sometimes the issue can be quite obvious, but sometimes it is more complex,' highlights Cosgrove. 'For example, if there is an excessive lateral compliance observed that does not present itself in an aligning test [in which the pads are rotated around the steering axis] we can eliminate toe compliance and suggest something to do with the wheel centre moving laterally.'

Developing and implementing K&C characteristics into a particular racecar is not a problem that has a single solution, and even amongst specific race series relatively large differences across the grid can be found. Performance parameters like camber and toe compliance are designed differently based on the design concept of each car. This is true even in series such as F1, where you might assume designs have converged to a similar solution.

» A K&C rig also has the useful ability to measure the c of g and polar moment of inertia of the car

PACE study

One example of a visitor to the K&C rig at MIRA was the Jaguar I-PACE eTrophy car. This programme used the rig to obtain what is in essence a K&C map, from which to make changes and modify aspects of the electric racecar's performance.

'For this season in particular, we focussed on the K&C performance of the car as we wanted to counteract some of the natural roll steer it has,' says Jack Lambert, lead development engineer for the I-PACE project. 'Because it is a road car, it has a natural kinematic understeer, so what we've done is actually introduce a level of compliance to the front axle to allow us to promote a more neutral balance through working with the kinematics of the car.

'Having that reference data set from the rig allows us to look at a set of numbers and surmise "I think it needs to do this" or "I think we need to alter this slightly", which led us to altering the front axle compliance, adding in compliance steer,' Lambert adds.

OEMs such as Jaguar also use their motorsport programmes to feed back into their road car designs, and the data from the rig at Horiba MIRA presented an opportunity to do exactly that: 'If we ever looked at doing a performance I-PACE, we can use that K&C data to understand the characteristics of this car,' continues Lambert. 'Maybe we can't run it at the ultimate capacity due to considerations around comfort and usability, but what we could do is bring in some of the performance capability to get more grip out of that road tyre.'

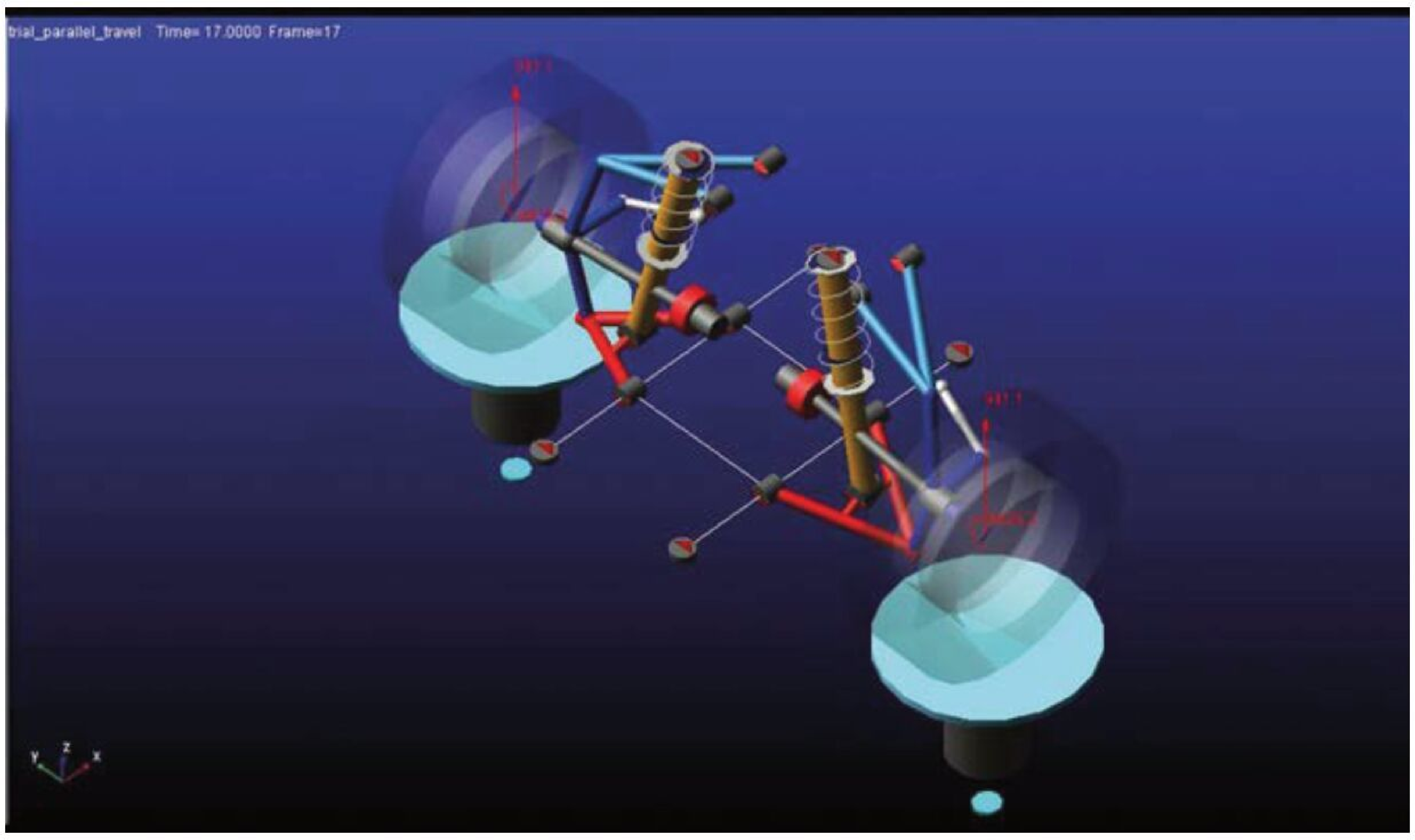
The K&C rig also has the useful ability to measure the c of g and polar moment of inertia of the car. Through monitoring loads measured during the action of pitching, heaving and yawing the body, the c of g location can be inferred and an x, y, z coordinate generated. The body can then be yawed around the c of g to deduce the polar moment of inertia in the y (vertical) axis, which affects the yaw acceleration of the car. This, again, can serve as a verification tool and generate a baseline or reference by which to measure future adjustments.

Defined by the architecture of the suspension, K&C characteristics are perhaps described as being inherent to each racecar. Once the car is assembled, there is limited opportunity to make adjustment. But a system that does offer important adjustability of dynamic performance post-design and build is the spring-damper unit, along with components such as anti-roll bars.

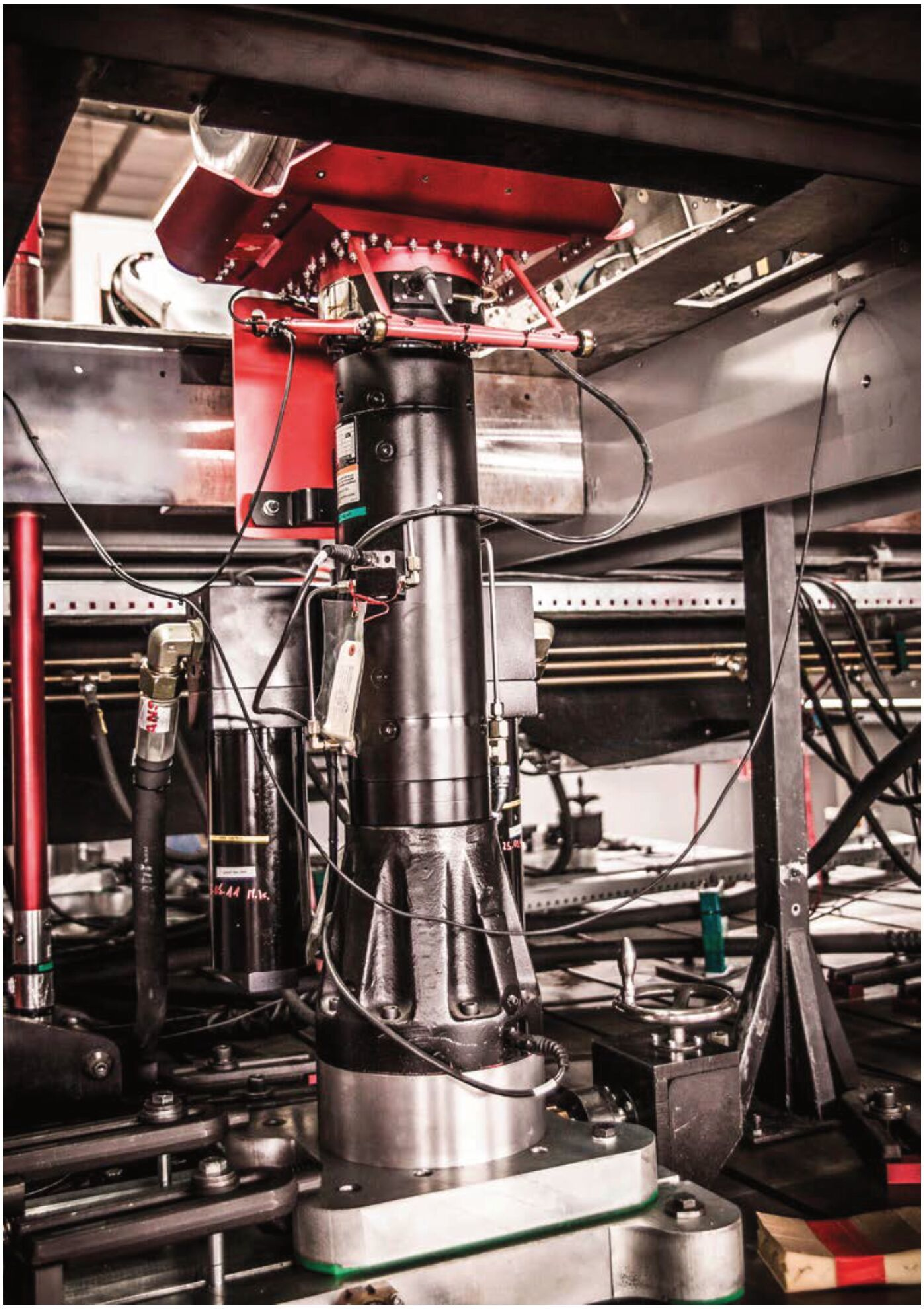
> **» Defined by the architecture of the suspension, K&C characteristics are best described as inherent to each racecar**

As loads are exerted on it, the spring stores potential energy, which it works to release, returning the system to equilibrium, which we consider as a specific ride height (changing with speed due to aerodynamic load). The damper then absorbs energy, controlling the rate in which the system can be restored to equilibrium by the spring. The magnitude of these effects are important as they have a fundamental influence on the vehicle dynamics of a racecar.

Maximising mechanical grip requires a supple spring-damper set-up to minimise variations in contact patch pressure whilst, at the other end of the spectrum, aerodynamic grip requires a stiff set-up in order to maintain ride height and reduce pitch and roll displacements to maximise the efficiency of the aerodynamic platform.



Virtual models are used to approximate the performance and allow quick assessment of dynamic parameters


TMG

Powerful hydraulic equipment is required for accurate testing, shown here beneath the floor of the seven-post rig at TMG

Ohlins USA

Damper manufacturers will use rigs for testing their new hardware developments. This is the Öhlins seven-post 'room'

TMG

Toyota Formula 1 car in the TMG facility. Seven-post rigs are vital when aerodynamic loads also need to be taken into account

The absolute rates of springs and dampers varies widely depending on the specific application. Absolute vehicle mass, CoM (centre of mass) location, aerodynamic loads, and peak accelerations (lateral and longitudinal) are the main considerations with track racing – off-track cars such as rally and rallycross vehicles must also consider course topology.

Finding the optimal set-up for any particular track can therefore feel somewhat like chasing a moving target as you work between cars and race series, so simulation in this scenario can be useful. Developments in analytical methods, once again involving multi-body software, has allowed valuable approximations to be made using computer simulations. Real, measured race track topology can be input into the virtual racecar model and allow virtual laps to be simulated. This generates data on damper displacements and allows histograms, peak cornering accelerations, yaw response, contact patch loads and all manner of other variables influencing the racecar performance to be outputted and scrutinised.

Full, accurate vehicle models are not always easy to obtain. They take considerable resource to create and it's not always feasible for a team to generate one. Inevitably, these are also not yet accurate enough that they don't require correlation with physical testing.

While linear or even progressive springs are easy to model, dampers and tyres are not so straightforward as they are highly non-linear in their response. Being an hydraulic system, a damper experiences losses that present themselves as hysteresis. The force produced by the damper at any given piston speed varies depending on its previous conditions. It is similar for tyres and their associated frequency response. Generating an accurate mathematical model is then not easy.

Furthermore, with considerations of time, expense, people and the desire for a controlled environment, track testing isn't the most efficient way to gather running data to feed back into improving a set-up either.

This opens the door once again to lab testing, providing the ability to measure accurate, quantitative data in a controlled environment with representative, repeatable inputs into a suspension system.

Rig for victory

Lab testing of whole vehicle vertical dynamics historically began on a machine known as a four-post rig, a device used by vehicle dynamicists to simulate vertical loadings and inputs into a vehicle. The shortcomings of such a rig were that it has no method of applying aerodynamic forces into the vehicle. For lower level motorsport this is not such a big issue, but for levels of motorsport featuring high-downforce designs these rigs are of little use, as the loads effected on the body directly influence the spring and damper rates required.

Technology evolved and added complexity, delivering it to where it is at the present time, with a system incorporating a further three input points to the body from which to simulate not only aerodynamic load, but also chassis heave, pitch and roll, enabling dynamic load transfer to be simulated. As a system, this provides all external loading to a vehicle suspension that can be expected in a reliable, measurable and repeatable way.

These seven-post rigs are generally used in the motorsport industry by vehicle dynamics consultancies, damper manufacturers and individual race teams for their racecar development. Inputting a simulated lap of a certain circuit into the vehicle via the rig actuators, engineers primarily measure contact patch pressure variation. Post-test data analyses might reveal areas requiring a tweak in compression damping, or maybe a stiffer spring rate might place the racecar into a better area of the aero map, for example.

Toyota Motorsport GmbH (TMG) is one company which has a seven-post rig in permanent use at its facility in Germany.

» [The 7-post rig] provides all the external loading to a vehicle suspension that can be expected in a reliable, measurable and repeatable way

» ‘After the test was completed, we found quite a few components from the racecar on the floor – brackets, bars and other random components’

‘We use our seven-post rig on all vehicles in our motorsport programmes,’ says Marco Gehlen, manager of vehicle and component Testing at TMG. ‘The main objectives with such testing are focussed on improvement of vertical dynamics, ultimately with the aim of reducing variation in tyre contact patch load for any given racing scenario. It is also an important tool for us in improving and developing the stability of the aerodynamic platform.’

Sim correlation

A further objective of seven-post rig testing is correlating the gathered data with simulation. This allows teams to assess very quick changes to the dynamic parameters of the virtual vehicle, greatly reducing development time and expense. Without this correlation work engineers can’t be sure the outputs of their virtual models are correct, and therefore can’t accurately evaluate changes made to a set-up.

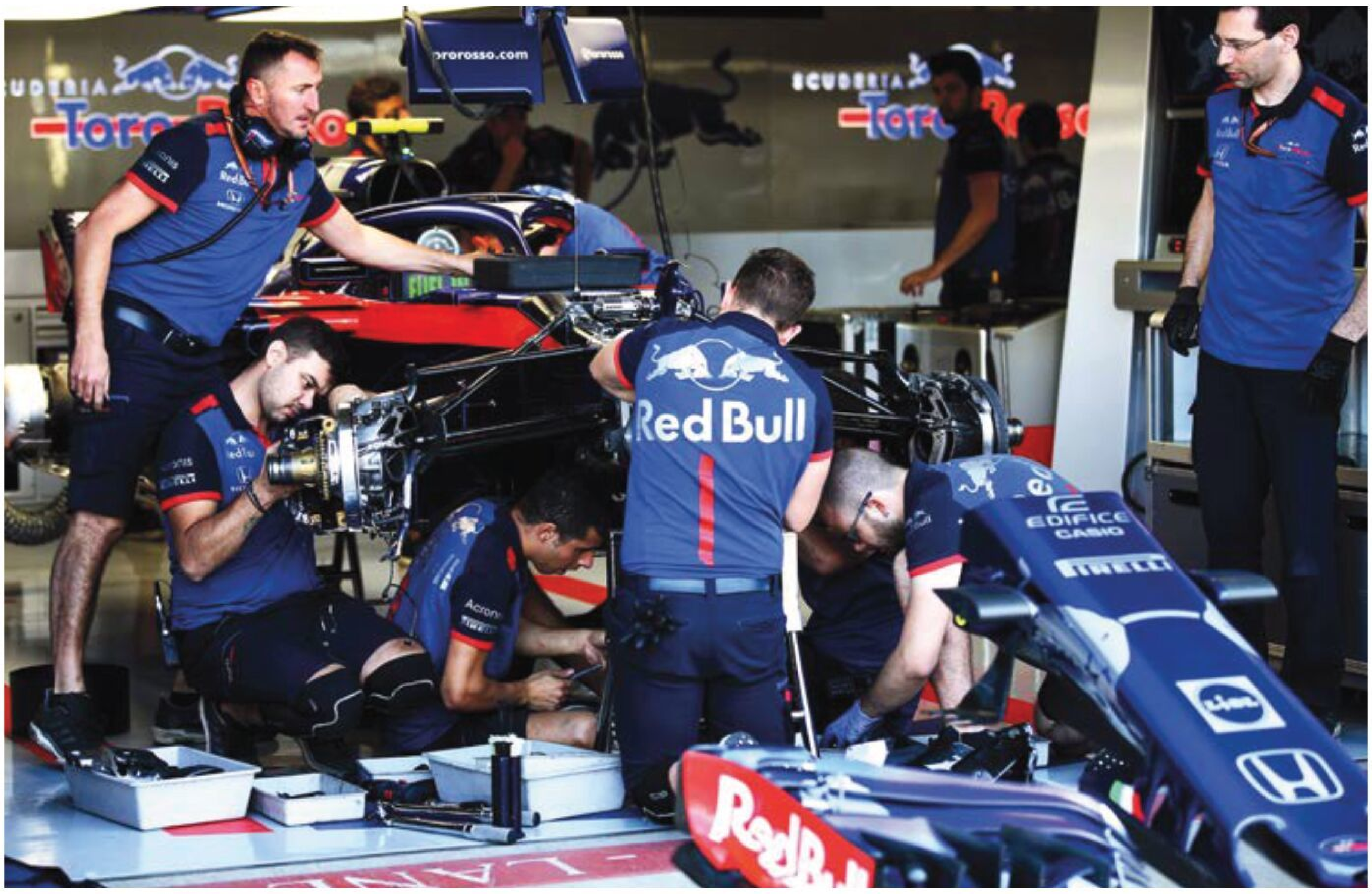
In addition to race teams, damper manufacturers also use seven-post rigs to development their technology. ‘We find benefit in using our seven-post rig in trialling various hardware iterations – different valving and internal components and such,’ says Christer Loow, technical director at Öhlins USA.

‘The advantage with these rigs over using single damper dynamometers is, for example, where you might wish to evaluate the effect of an increase in damping rate. With a rig or on track you’ll naturally see a reduction in damper displacement associated with this, but with a damper dyno the actuator is providing input based on displacement rather than force, so you see the same displacement regardless of the damping rate. This is, of course, an unrealistic scenario, which won’t provide valid data any more and can even damage the unit.’

An iterative process is usually followed as the testing progresses, beginning with simple frequency sweeps, progressing to more complicated road input data measured from race conditions as confidence in data is gained.

Adding complexity

‘Generally, we try and get the cars on the rig as early as possible to obtain a baseline for the car and verify our initial simulation predictions,’ says TMG’s Gehlen. ‘We start with easy inputs such as low frequency sine waves for initial correlation, then we start adding complexity with further inputs such as downforce actuators. We then check the correlation once more and make any adjustments necessary to the virtual model, we do this process step by step until we have reasonable correlation for the simple frequency sweeps. This then gives us confidence to use track data with the rig.



For F1 teams, hard graft on the seven-post rig at the factory means less works needs to be done at the race track

‘One of the considerations for the seven-post rig is with understanding the vertical stiffness of the tyre,’ Gehlen adds. ‘For example, the vertical stiffness of a tyre rotating at 250km/h is known, but on the rig the wheels are not rotating and so we must compensate for the loss in stiffness with inflation pressures. Of course, what we can’t match in a lab is the hysteresis of a rotating tyre. There is not much we can do to compensate for that with a static tyre, so this is something we have to work around.’

Acceptable correlation is usually defined by an acceptance criteria. In the case of TMG, error in the RMS (root mean square) of contact patch force between track measured results and rig measured results is used. ‘Generally, once two sets of data match to within 20 per cent, we class this as acceptable,’ Gehlen tells us.

‘For correlation to virtual models, you’ll need several test sessions, each around a week long,’ Gehlen adds. ‘On the other hand, if a customer only wishes to understand where their car is currently operating, and to make physical changes based on that, they are usually happy with results gathered in a five-day test schedule.’

The rig also brings advantages in that you can implement and trial changes that might perhaps be a little unconventional, or carry a certain risk if it went straight on to the track

‘A lot of our IndyCar customers use inerters, which have the tendency to make the car react very harshly to bumps on the track. They can also have a negative impact with kerb strikes,’ notes Loow. ‘It may be risky to go straight to the track with a very high inertance without a sufficient damper blow-off setting. The rigs can act as a proof of concept in this sense.’

You also start to gain experience around what ‘looks right’ in the sense of good data, which allows you to fault find and save valuable time. ‘If there is excessive friction somewhere in the system, or a damper has failed you, learn what that looks like in the data. This helps teams with fault finding and issue diagnosis, as you can spot issues very quickly in the data where it can maybe take a whole day of track testing to focus in on that issue,’ Loow says.

All shook up

While seven-post rigs are generally not used to run durability testing on vehicles they do, by definition, place a lot of stress onto chassis and body components, as one TMG client discovered: ‘One customer recently asked us to run a test with input data for the [Nürburgring] Nordschleife on their racecar,’ says Gehlen. ‘After the test was completed, we found quite a few components from the car on the floor – brackets, bars and other random components. This was very surprising for them, and it was certainly a benefit that they tested on our rig before they went on the track.’

Rig testing is not especially new, but in modern motorsport it is certainly now extensive, offering engineers a whole new dimension of information from their racecars. They are now an invaluable piece of equipment in the toolbox of vehicle dynamicists at all levels of motorsport. As a profession, we rely more and more on quantitative analysis techniques to find minute increments in performance, and so rig testing is certain to remain prominent in shaping and evolving motor racing in years to come.

MINIATURE HYDRAULIC SYSTEMS FOR GLOBAL MOTORSPORT

MOOG

CLUTCH CONTROL | DIFFERENTIAL CONTROL | REAR BRAKE PRESSURE LIMITING | THROTTLE ACTUATION | POWER ASSISTED STEERING | ACTIVE RIDE HEIGHT CONTROL | TURBOCHARGER WASTE-GATE CONTROL | GEARBOX ACTUATION | DAMPER CONTROL | REAR WING ACTUATION | INLET TRUMPET CONTROL

FORMULA 1 WEC HYPER CAR WRC SIM & TEST TIER 2

Moog high-performance motion control solutions and components have been at the forefront of sub-miniature actuation systems in motorsport since 1982. Over the intervening years, Moog has continuously developed its range of leading products and systems for actuation in many motorsport sectors including Formula 1, World Rally Championship (WRC), Moto GP, Touring Cars, and Le Mans hyper car prototypes.

Today, Moog also offers customised simulation and test motion control solutions with combined motion mechanism, control loading system, complete software package, cockpit and a dedicated operator workstation.

Visit moog.com/motorsport

Miniature Servo Valves and Controllers | Power Assisted Steering Valves | Actuators | Fuel and Oil Pressure Regulating Valves | Brushed and Brushless Motors | Brake System Failsafe Switching Valves | Cartridge Direct Drive Valve (DDV) | Miniature Hydraulic Power Units | Precision Ball Screws | Integrated Motorsport Systems | Driver Simulation and Test Systems

Moog_Industrial **moog-in-the-uk**

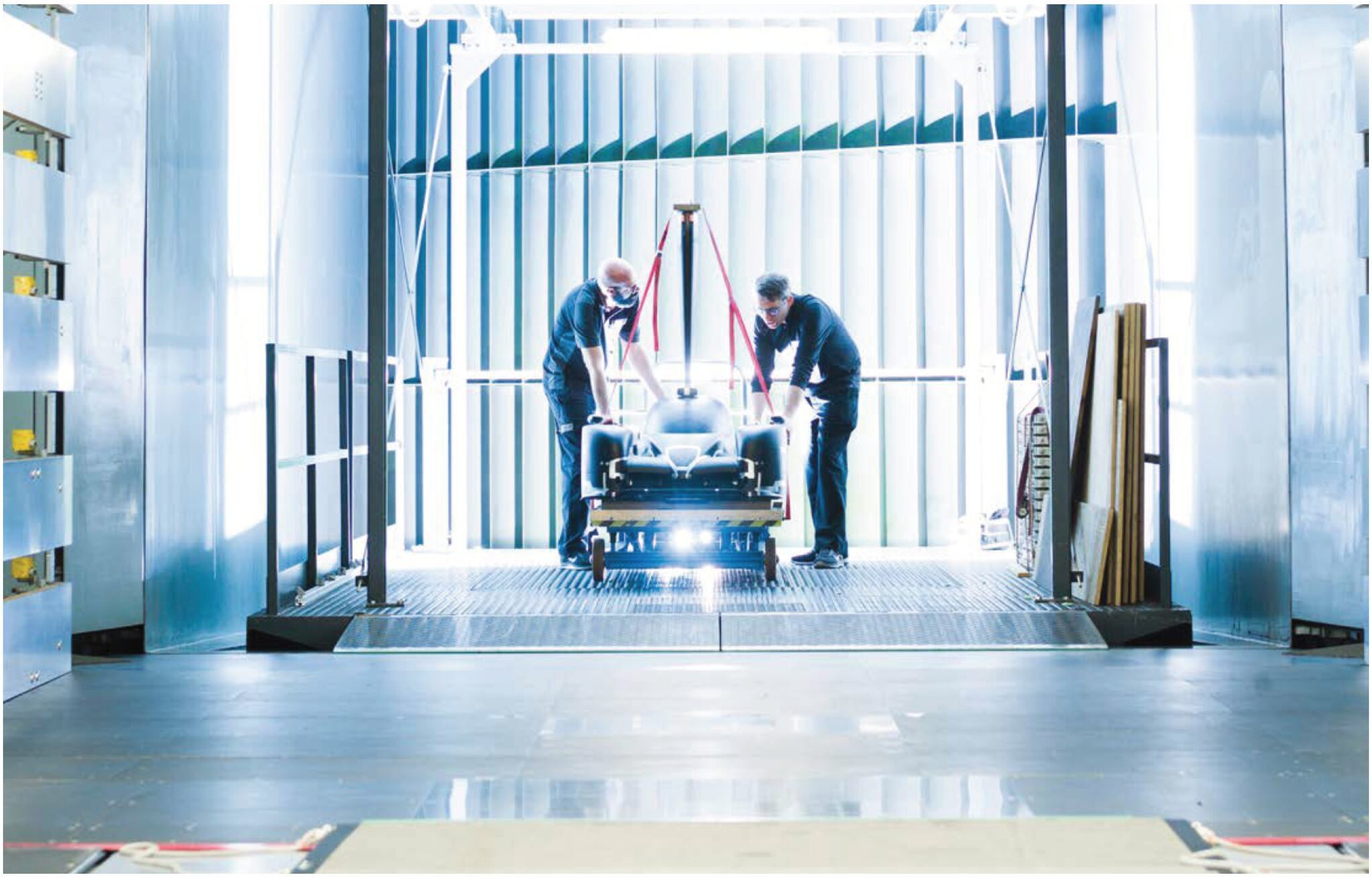
MotionControlVideo **moogintheuk**

FORMULA 1, F1, GRAND PRIX and related marks are trade marks of Formula One Licensing BV, a Formula 1 company. All rights reserved.

MOOG GLOBAL SUPPORT®

moog.com/motorsport

MOOG



TGR

Model behaviour

Understanding the benefits and limitations of scale model wind tunnel programmes

By JAHEE CAMPBELL-BRENNAN

Wind tunnel testing has a fascinating history, beginning in the aerospace industry. As testing methods became more sophisticated and laboratory testing evolved, a need was identified to provide a method of validating design concepts. The Wright brothers were the first to achieve controlled flight as they built a tunnel to calibrate the characteristics of wing profiles and showed that the accepted characteristics were wrong.

However, few tunnels existed that would be capable of managing a 1:1 scale prototype. Aerospace engineers quickly figured out there were many advantages to preparing scale models. Namely, it enabled testing to take place at all, but furthermore cost, materials use and build times were slashed when compared to full-size prototypes.

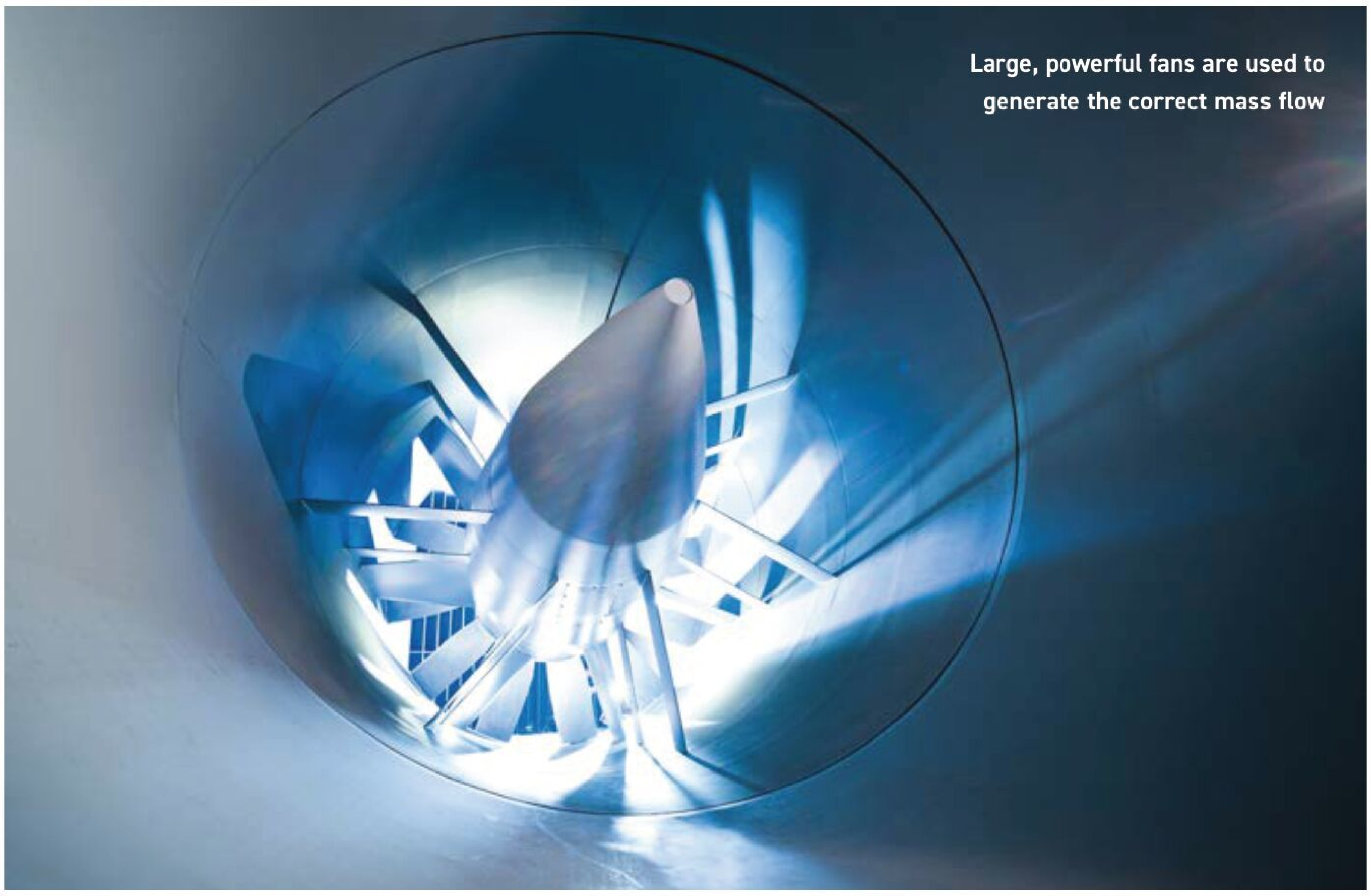
Cars by their very nature operate close to, and in contact with, the ground, so automotive wind tunnels differ substantially in design to aerospace ones. A moving ground plane and effective boundary layer control are critical features but, in the early days of automotive wind tunnel testing, these weren't available to full-size models. The concept of scale models within automotive and motorsport testing was therefore born out of similar necessity to aerospace.

A modern automotive wind tunnel's principal function is to accurately recreate the motion of a car driving on a road surface. The key difference experimentally, however, is that you are moving the air over the vehicle, rather than moving the vehicle through the air. At a minimum this requires the presence of a relative air velocity over the car body, and a moving ground plane to simulate the asphalt passing beneath.

Matched relationship

The relationship between tunnel and model is a valuable point of learning as they must be matched in order to create a suitable test environment. So, from an engineering point of view, the particular tunnel facilities available for a project tend to decide the maximum scale of model used. Let's explore what that means in practice.

When testing in any wind tunnel you have a fixed cross-sectional area. Naturally, the presence of a test model introduces a flow


Large, powerful fans are used to generate the correct mass flow

TGR

» **The scale of the model ultimately dictates the air speed, and for this reason it's usually a case of 'the bigger the better'**

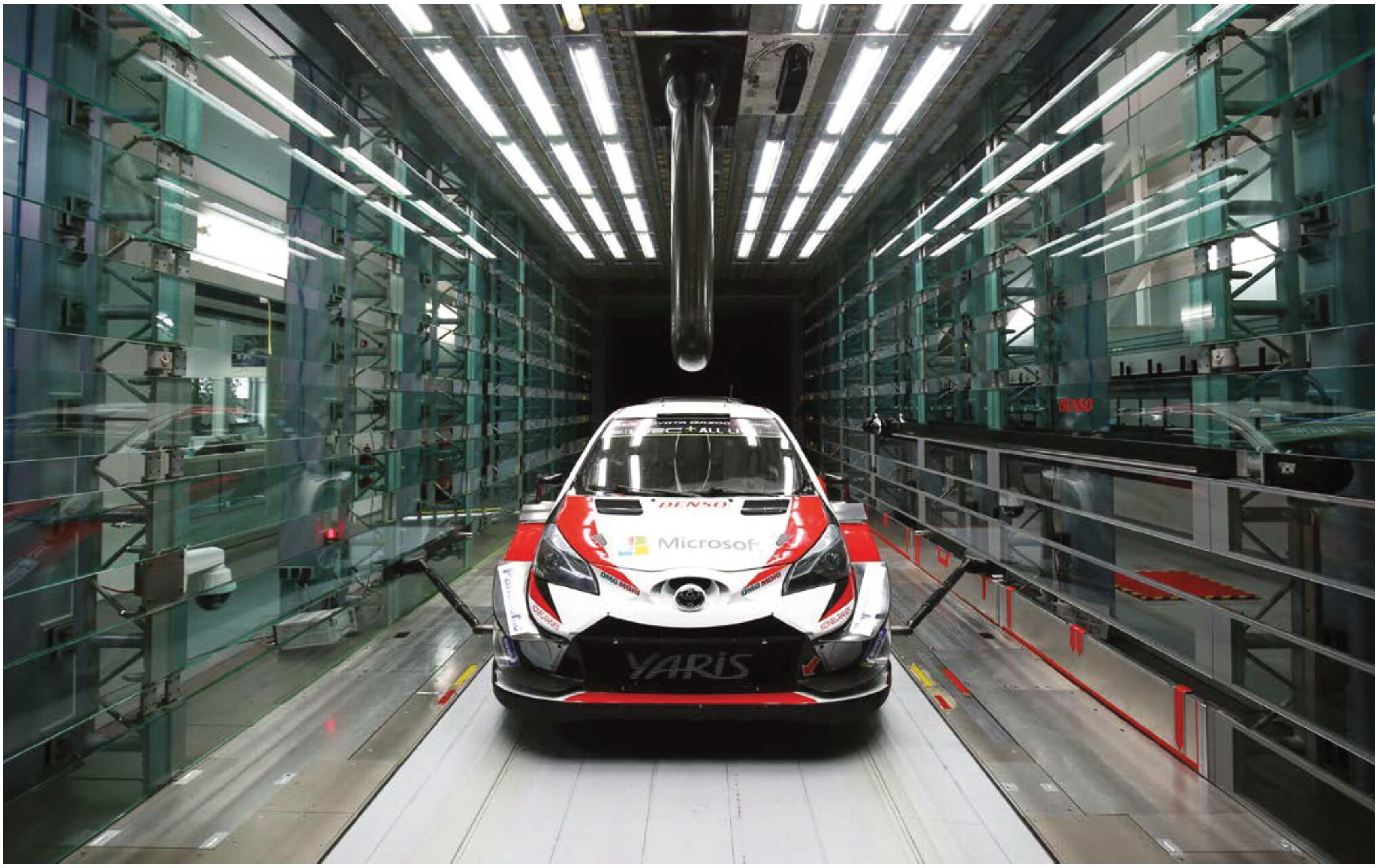
constriction into the tunnel. The presence of the flow constriction can manifest in two ways – either as a solid blockage, attributed to the frontal area of the vehicle, or wake blockage, which occurs when the dispersion of turbulent wake from the body is impinged by the roof and side walls of the tunnel. The design of the tunnel does have influence into how significant these effects are, but they are inescapable.

Solid blockage is problematic as it causes local increases in velocity around the vehicle body. Due to the principles of continuity (Bernoulli), flow travelling through a constriction must increase in velocity to preserve mass flow. The static pressure around the car body therefore lowers and the measured forces around the body become skewed. The result are therefore invalid.

Wake blockage is a little different as it's not directly a result of the model's area but, due to its geometry, will generate a turbulent wake in the tunnel. Interfering with the wake flow affects the pressure distribution across the whole body. The rear wing and diffuser can be particularly sensitive to this as pressure distribution and mass flow are impacted, which means the point of flow separation can be altered.

'Wake blockage can be an issue with larger test models. When the wake is very large, the flow can affect the breather, where tunnel pressure equilibrium is maintained. If the wake is too big it can also affect your pressure distribution across the test section,' says René Hilhorst, chief of aerodynamics at Toyota Gazoo Racing. 'Depending on the design and whether the splitter, rear wing or diffuser are strong in generating downforce, it can affect those to a greater degree, but it really does affect the whole car.'

The section, or blockage ratio (tunnel cross section vs test piece frontal area) is usually maintained at below 10 per cent. Although a blockage as low as is practically possible is desired, it's always necessary to incorporate


TGR

Toyota Gazoo Racing's custom wind tunnel facility was built with a slotted test section and optimised for 60 per cent scale models, though will also fit full-size vehicles

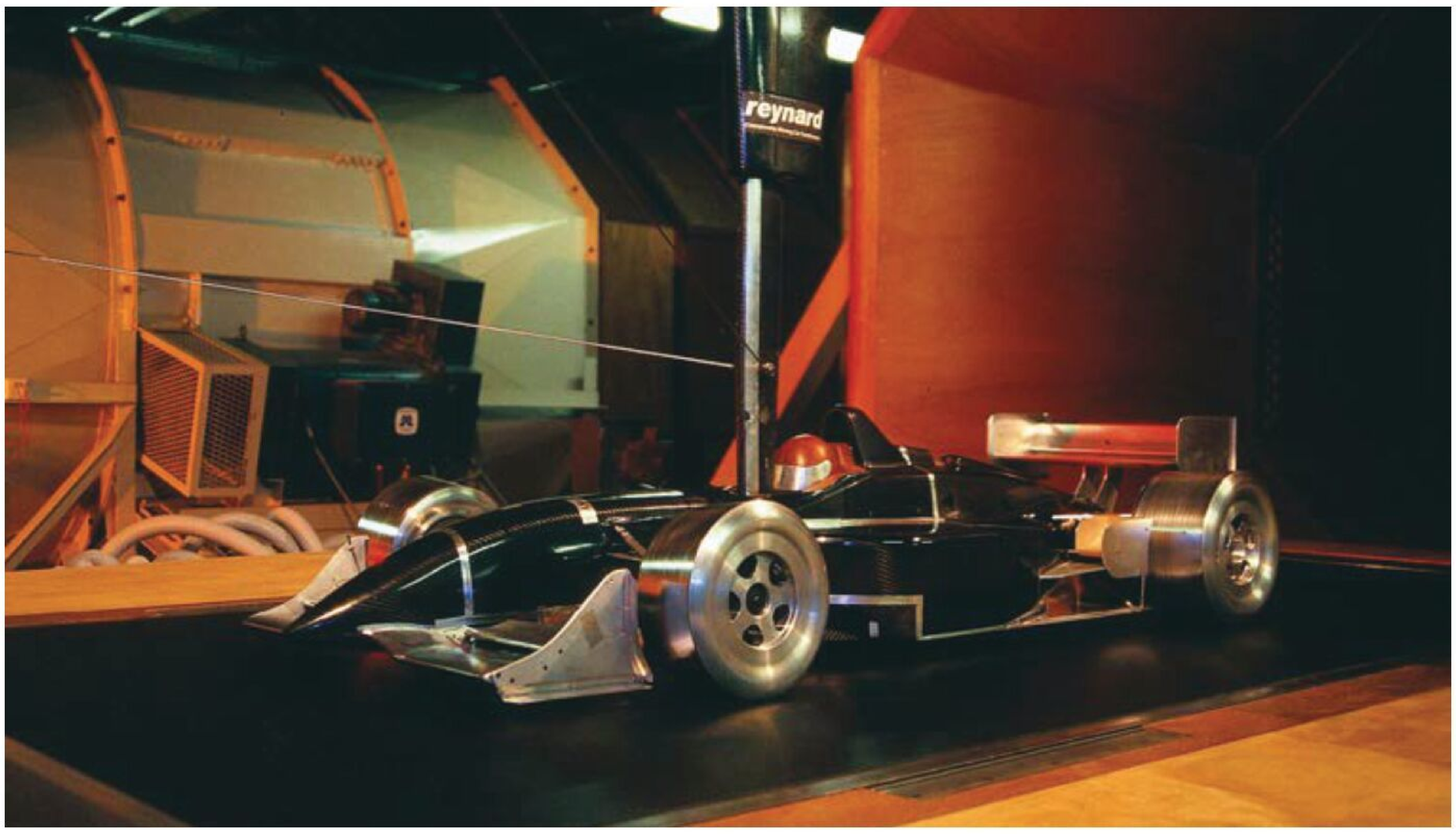
Scale models for high-level motorsport are highly refined and feature all the dynamic complexities of the full vehicle

> **» '[Scale models are] generally now a mixture of polymer, sintered metallic parts and metal reinforced polymers'**
>
> René Hilhorst, chief of aerodynamics at Toyota Gazoo Racing

blockage corrections into any measured lift and drag coefficients to adjust for local velocity and pressure gradient influences. The actual correction arithmetic can be fairly complex and proprietary to a particular tunnel, but it's important to remember this is not a problem specific to scale model testing.

As we'll discover a little further into the article, the scale of the model ultimately dictates the air speed around it, and for this reason it's usually a case of 'the bigger the better' when referring to scale.

'The tunnel at Toyota Gazoo Racing [TGR] was built for F1,' adds Hilhorst. 'The main target was to have exceptional conditions for scale model testing up to 60 per cent, and capability to do very good full-scale testing, but we don't do this so often.'



Models can also be relatively simple and static, but still reveal meaningful data

Levels of complexity

So now we understand some of the elementary concerns of wind tunnel testing, let's take a look into the detail of the scale model and what's required from it to produce meaningful data for the aerodynamicist.

The model itself is a pretty elaborate component as it must be intricate to be representative. In all but the simplest test cases, the model must incorporate all the degrees of freedom [DoF] a real car has – wheel rotation, steering, body and suspension movement (with accurate kinematics), ride heights, chassis pitch, roll and so on. And that doesn't even touch on secondary effects such as aeroelasticity and tyre squish due to aero load. It can quickly become an extremely complex item.

Of course, the actual racecar is the perfect instrument in this sense, so how do you incorporate these features of a real car into a model? And more importantly, what determines the level of complexity required of a model for a particular project?

'There are clear differences in model complexity as you get to more high profile championship levels, and therefore bigger budgets. The more basic models will not have any kind of ride height actuation or steering capability, and will likely have solid tyres,' comments Dominic Harlow, a motorsport engineer director of engineering consultancy, Dominic Harlow Consulting. 'When you get to Formula 1 territory, however, you've got pneumatic tyres, full DoF of suspension movement and ride height actuation, right down to the pre-loading of tyres to represent the effect of aero load.

'Prices then can go from £50k [approx. $63,425 / €55,425] for something like a 30-40 per cent [scale] F3-style model up to around £500k [approx. $634,250 / €554,250] for an F1 model.'

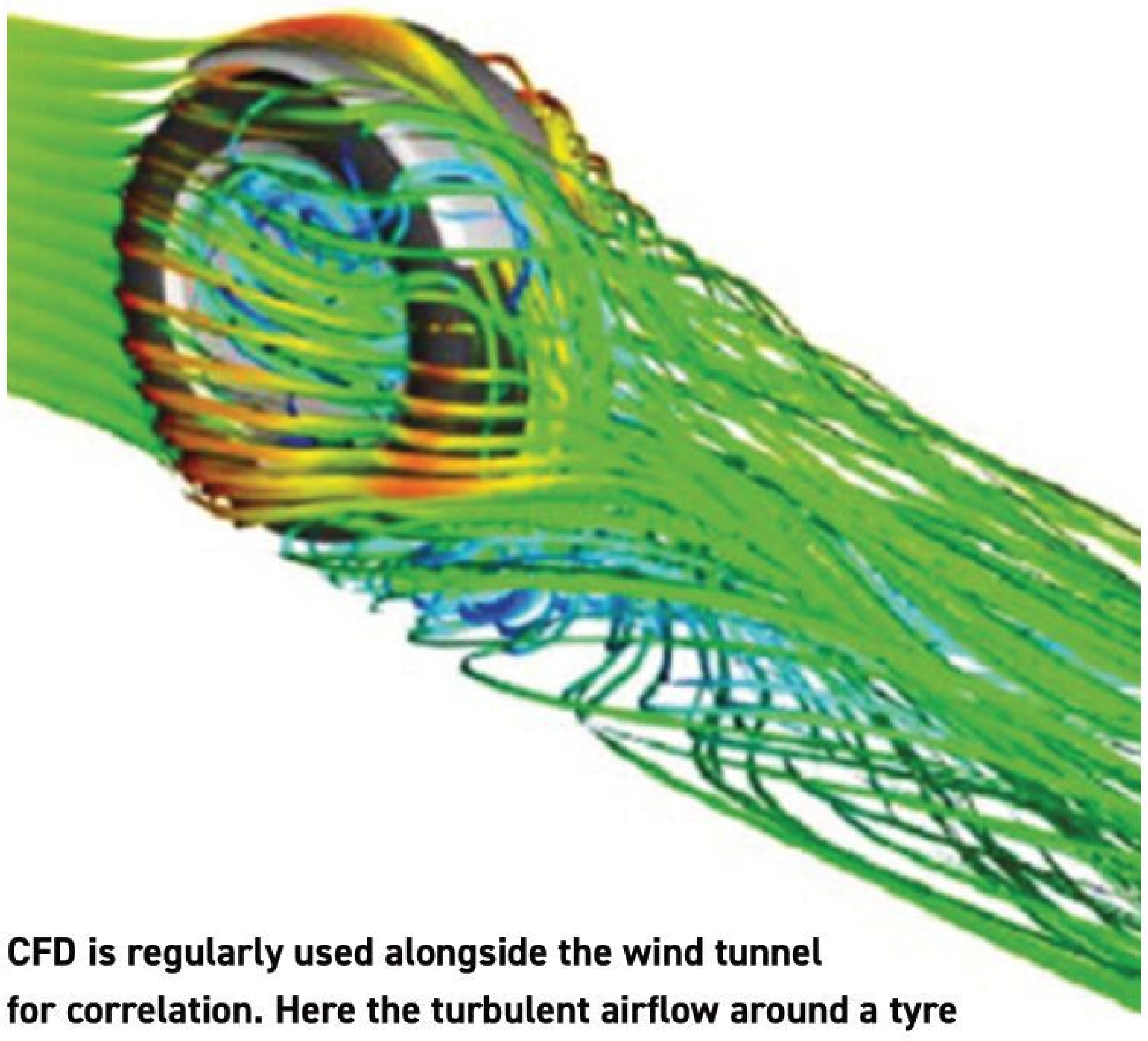
Hilhorst adds: 'When we were competing with Audi and Porsche in the WEC, the level of detail required was close to F1 level. We had to go into very refined models with lots of data acquisition and sensing to find the maximum information possible. When you are doing development for a project with less intense competition, you might focus more on styling, where the model detail might be less important, so it's chosen accordingly.'

Added detail

Features requiring actuation, such as steering and ride height adjustment, are usually achieved using linear actuators and motors. By extending or collapsing the length of a push rod, the ride height or pitch and roll of the model can be adjusted. Likewise, a steering rack can be represented to actuate the steering arms of the model. Tyres add another level of detail to the picture.

TGR

Pre-load can be added to scaled tyres to imitate squish due to aerodynamic loads. In some cases, tyre manufacturers will make scale models of their products for wind tunnel testing



CFD is regularly used alongside the wind tunnel for correlation. Here the turbulent airflow around a tyre

» As a pneumatic device with its own spring rate, the shape of the tyre varies dynamically with air speed and the subsequent aerodynamic loads that result

As a pneumatic device with its own spring rate, the shape of the tyre varies dynamically with air speed and the subsequent aerodynamic loads that result. In certain applications, this has a huge influence on aerodynamic behaviour, particularly at the contact patch where air is 'squished' outwards as the wheel advances forward. Tyres, especially with open wheelers, generate quite considerable lift and drag forces too, which are of interest to aerodynamicists.

Let's add some context to this and imagine the airflow over an open wheeler. Turbulent flow structures coming off pitching and rolling front wings, deforming tyres and turning wheels have a huge potential to interact with downstream performance parts such as bargeboards, underfloor and rear wings. Closed-wheel cars are affected due to the tyres influence on underbody flow, although not to the same degree.

To provide an accurate means of modelling this on a scale model, tyre manufacturers, at least at higher levels of motorsport, actually make scale versions of tyres with matched physical properties to their real counterparts (see *RE* V23N11).

'We like to understand the contribution of the tyres to overall forces. As the tyres are attached to the model and we are running rubber tyres, we must measure the lift and drag contributions from those also. As you get into more detail around aerodynamic behaviour, you see that the deformation of the tyre patch is important to overall aerodynamic behaviour, and is very dynamic, so we try to be as accurate with this as possible,' adds Hilhorst.

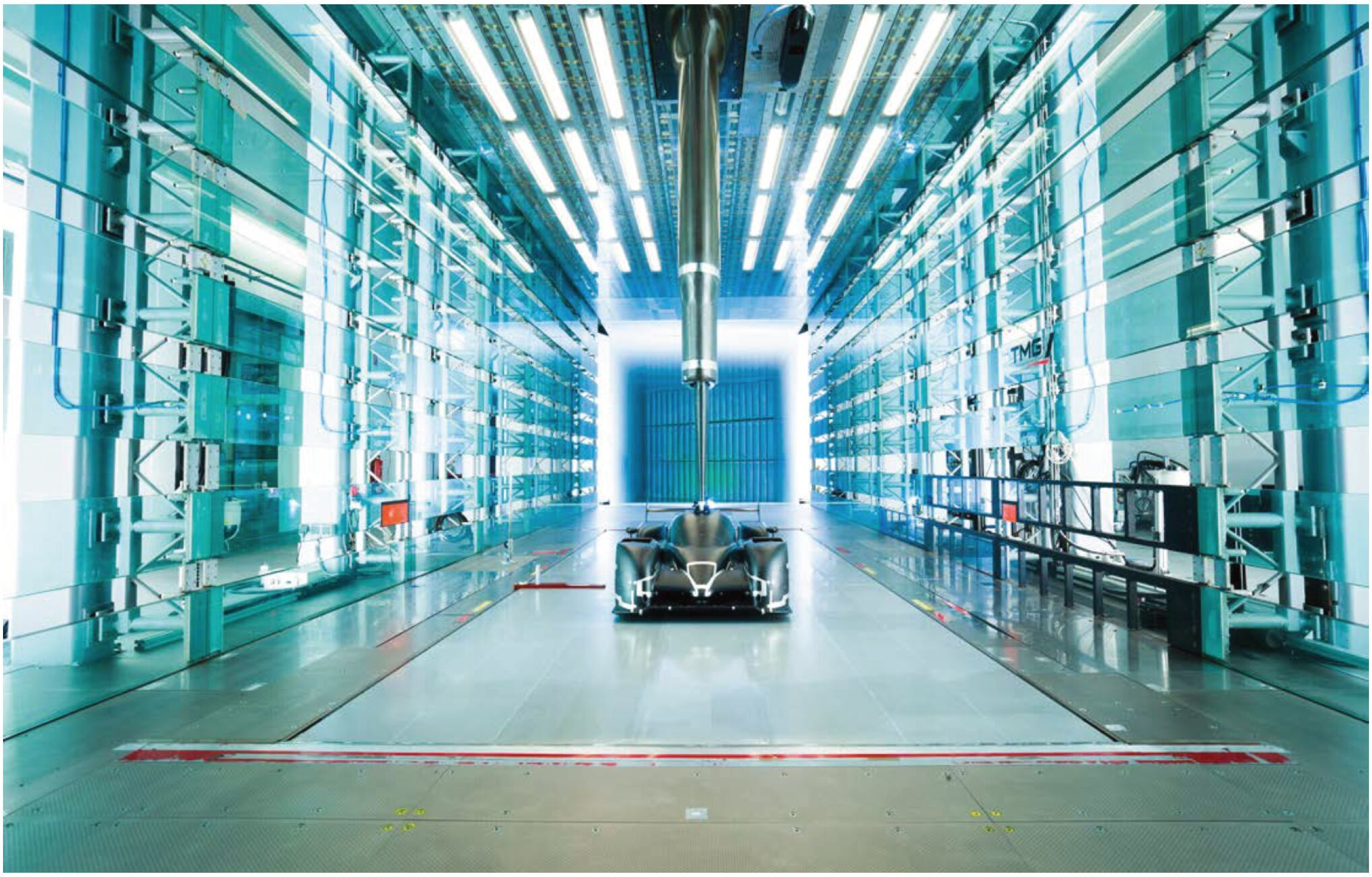
A GT platform, for example, simply wouldn't require the same level of detail.

Rapid modelling

In their construction, scale models have taken huge leaps forward in terms of technology in recent years, particularly with the advancement of rapid prototyping technology. In the past, model aerodynamic surfaces were constructed from carbon fibre with an aluminium inner skeleton to provide structure, but now it's a different world.

'Since the explosion of rapid prototype manufacturing, in terms of printing techniques and quality, we are now enabled to use this technology in our model construction,' explains Hilhorst. 'It depends on the specific load requirements of the structure, but is generally now a mixture of polymer, sintered metallic parts and metal reinforced polymers. There's just so much development that has happened over the last few years, it's fantastic.'

The ability to rapid prototype engineering solutions has unlocked an entirely different approach to prototype production and revolutionised testing. 'We can go straight from CAD to the machines, which means we can have a model completed in a very short time. Typically, a few days, but if there is a real emergency and all our machines are free, we can make this happen overnight.



TGR

With similitude, boundary layer control and a moving ground plane, TGR has seen accurate correlation between wind tunnel models and the full-size car

'This capacity and capability exists as a carry-on from our time in F1,' says Hilhorst.

That is in sharp contrast to the several months it can take to construct a model using the more traditional techniques.

It is interesting here to note the relationship between model size and material usage. As volume is a cubic function, it follows that a part made at 50 per cent scale is using 12.5 percent the quantity of material. Likewise, 6.4 percent for a 40 percent model and 21.6 per cent for a 60 percent scale model. Mass follows the same trend, and this is an important consideration for material usage and the associated costs of machining, which can be factored into the scale one might choose for a project.

Dynamic similitude

Earlier, we touched on the fact that flow speed has to change with scale. Assuming you want to maintain the same relative flow speed over the model surfaces, when you halve the scale, you might think you halve the speed. In fact, the opposite is true.

The engineering behind this is focussed around a concept called dynamic similitude. In this context, similitude demonstrates that the flow conditions between the model and the real application are analogous but, in an absolute sense, they are different. Again, this is a concept the aerospace industry had to tackle long before automotive. Since in motorsport we are dealing with low flow velocities that we can consider them to be incompressible, it means we can ignore the effects of Mach number and need only look at the Reynolds number.

The Reynolds number of a flow defines its regime – either laminar or turbulent. It relates the inertial forces generated by the fluid molecules as they collide and alter direction to the viscous forces generated by shear stresses generated during internal friction.

In principle, this is an indication of the point at which a flow can be expected to transition from laminar to turbulent.

Its relationship with flow speed is perhaps easier to see via this equation:

$$Re = \rho u L / \mu$$

Since fluid density (ρ) and dynamic fluid viscosity (μ) are constant in cases within automotive wind tunnel and L, the reference length section, is determined by the model scale, the equation shows us that any reduction in scale can only be balanced by an increase in flow velocity (u). A simple mathematical problem ultimately.

The Reynolds number becomes really useful in understanding flow over items such as wings, underbodies and diffusers. When the ratio of inertial and viscous forces reaches a certain threshold, and the momentum possessed by the fluid exceeds the effects of the viscosity in keeping the flow laminar, it indicates the flow is turbulent. This is crucial when ensuring flow separations and vortices are happening on both the scale model and at full size in the same manner. This relationship is what must be maintained in achieving similitude. In short, what this tells us is that a 50 per cent scale model requires double the air speed to achieve similitude.

In a real sense, this means a 'real life' 70m/s airflow becomes a wind tunnel air speed of 140m/s (313mph / 504kph). You might not only struggle to find a wind tunnel with the power to generate that level of flow and ground plane speed, but with even smaller models you also start to enter a realm where the Mach number is large enough that air

> » **'We can go straight from CAD to the machines, which means we can have a model completed in a very short time. Typically, a few days'**
>
> René Hilhorst

cannot be considered incompressible any longer. At this point it all starts to unravel.

On paper, you can get around this issue by pressurising the tunnel, or using a 'heavy' gas, but I'm not aware of any automotive tunnels that do anything like that.

Despite efforts to match the Reynolds number in a particular test, there are other factors that need to be considered in order to effectively correlate wind tunnel tests to a scale model, as Harlow explains:

'There can be times where you're especially sensitive to Reynolds number. For example, front wing ride height sensitivity. You can get into a situation where your wind tunnel data looks very favourable in a particular scenario, but which would ultimately lead to separation and stall at the track, so is therefore not representative.

'Sometimes subjectivity and experience come into play there. Reynolds number is all about the transition from laminar to turbulent, and then separation, and ultimately how close that is to reality.'

TGR's experience also reflects this reality. 'With scale models, by definition you are not at the same Reynolds number as the real car at the same speed, so you always have to accept a slight difference in Reynolds number. Through correlation you must make sure the flow structure is not affected by this difference. Even then, sometimes a model will follow a slightly different flow pattern and give you a different result. Because of this, some parts that work in the wind tunnel don't perform as suggested in real life,' notes Hilhorst. 'This can be due to things such as surface finish, model quality and detail, aeroelasticity… It can be a number of reasons. When we discover this, we go back and change the model, but sometimes it will still never truly match.'

Surface finish

One particularly interesting concept is the effect the surface finish of a model can have on the measured drag, and the way in which a part generates lift. In this case, the finish of an aerodynamic surface has influence on the boundary layer of flow over the part. A rougher surface can induce flow separation earlier than a smooth part would, although a rougher surface can also trip the boundary layer flow from laminar to turbulent, which is more robust and can *prevent* separation.

'If you take a part straight from rapid prototyping and measure its performance without performing any finishing, then polish or paint the part, you will always measure something different. This effect can be significant, not only affecting skin friction but also lift,' confirms Hilhorst.

For practical reasons, wind tunnels operate at a fixed speed / Reynolds number during any set test. The actual test speed is generally chosen to give the largest benefit for a particular driving scenario, usually determined statistically.

» A scale model must be constructed in such a manner that there are representative levels of flex at peak loads

60 per cent models can look more like 30 per cent scale to the naked eye due to the way we view area

'A car drives at an enormous range of speeds at any track, so you have to find a way to determine what speed and attitude you'd like to represent in the tunnel. Usually this is determined with an element of subjectivity, but there's also an element of data using statistical analysis ie at what speed does the car spend the most time, correlated with where you generate the most lap time. Where those two things are at maximum is where you tend to focus development,' says Harlow.

This data can be taken from lap time simulations or measured data.

The science of aeroelasticity is also an important consideration with scale models, which gives consideration to the interaction of aerodynamic forces on structures. As a generalisation, it's not a design feature to have aerodynamic surfaces flexing (unless you were in F1 circa 2012). Jokes aside, a scale model must be constructed in such a manner that there are representative levels of flex at peak loads. A rear wing that flexes can alter its angle of attack, an underfloor that bows towards the ground can stall the diffuser. It's an important thing to get right if you're to rely on the wind tunnel results.

'Aeroelasticity, in the context of ensuring the scale model has representative physical properties to the real car in terms of stiffness, becomes trickier as you go up in scale and test speed as you're generally not using the same materials,' says Harlow. 'This is why a lot of F1 teams use metal-coated, rapid-prototyped parts, especially when they're very small and intricate.'

It's common process to match the stiffnesses between the scale model and real car at your chosen design speed. With this methodology, you enable the deflections at particular Reynolds numbers to be identical. Small steps like this are really necessary when you're trying to realise a strong correlation between the two cases.

Aerodynamic loading

On the subject of aerodynamic loads, how do they compare between scale model and full size? To understand this, it's important to remember that the peak loading of an aerodynamic structure is dependent on the area of surface the pressure is working on. As we know, area is a squared quantity, so it's quite a simple move to 'scale up' (or down, depending) the forces to suit.

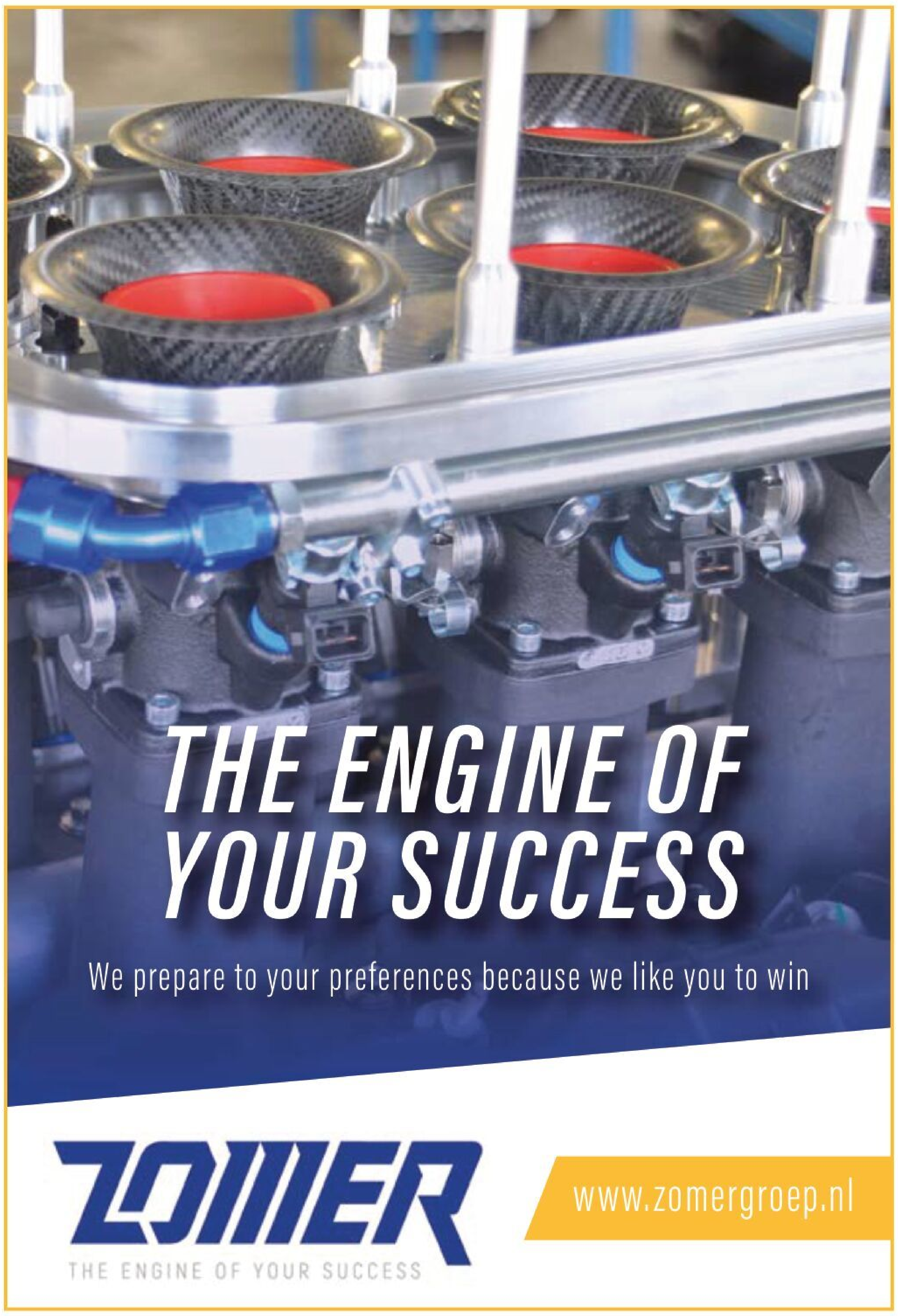
This information is useful on two fronts. In the design and build of the model you need to understand the magnitude of forces it's likely to encounter for precisely these concerns of strength and aeroelasticity. Then, when you've completed testing, you need to understand how the values recorded in the tunnel compare to the full-size vehicle.

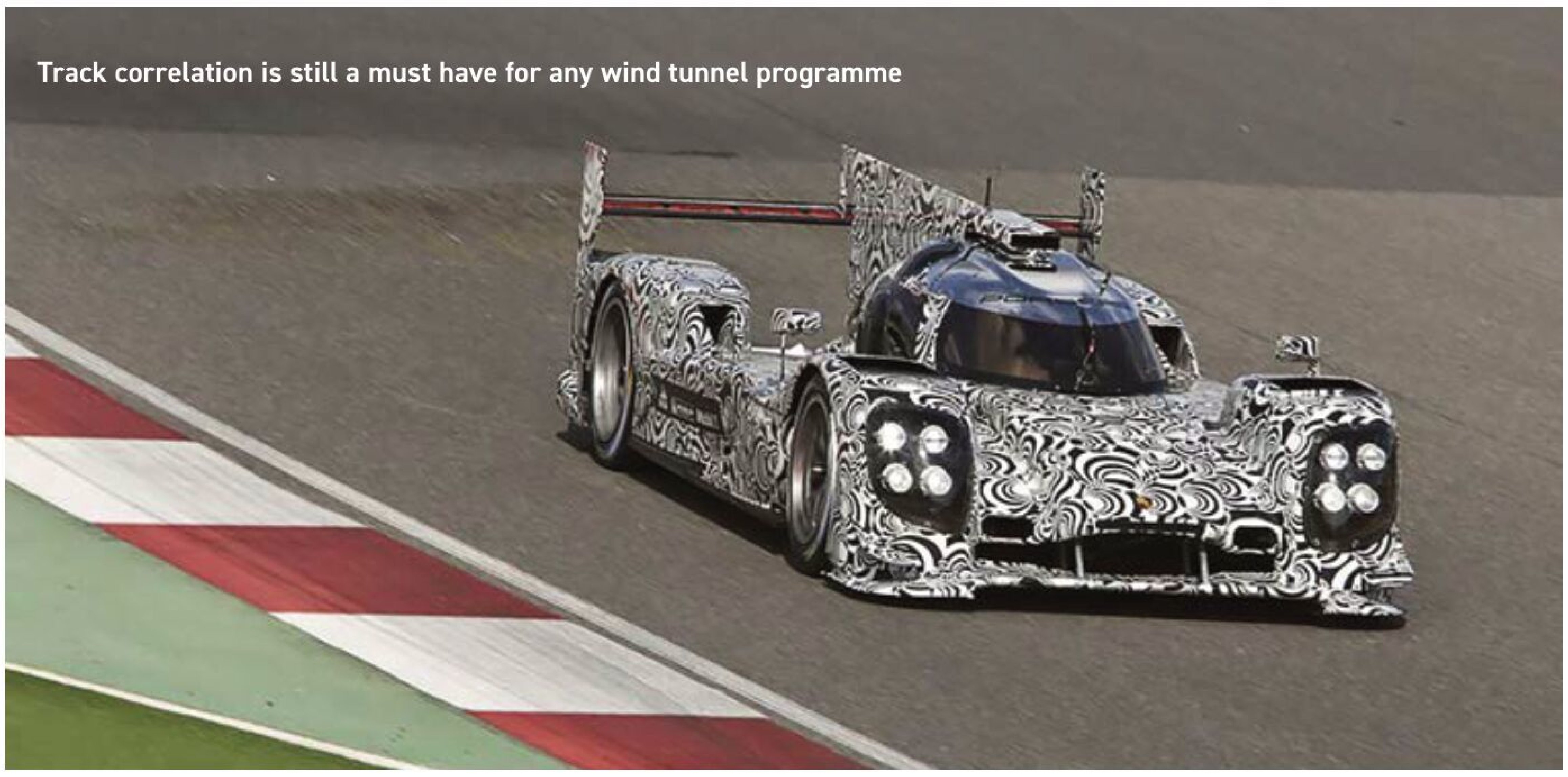
To explain this with a little mathematics again: take any given speed, say 40m/s. The forces on a 50 per cent model are 25 per cent (0.25) of the full-size model, a 60 per cent scale model gives 36 per cent of the forces, and so on. To work the other way and relate model forces to the full-size car, use the inverse. At similitude, the forces are the same on both scale and full size.

Area 36

This relationship of areas is interesting. If you've ever seen a scale model in person, they can look really quite small in a way that initially doesn't make sense. When we view objects, any object, we're actually looking at the area, which explains why a 60 per cent model looks more like a 30 per cent model because we're only viewing 36 per cent of the full-size area.

The actual testing methods of scale models don't differ substantially to their full-size counterparts. It starts with understanding the operating envelope of the car and each feature of the model that is adjustable. Then we look at the range of attitudes that are likely to be seen on the track, and any





Track correlation is still a must have for any wind tunnel programme

Porsche

» 'A wind tunnel is a different picture of the truth and needs a lot of energy to ensure good correlation'

David Floury, technical director at ORECA

specific areas which demand particular focus. For example, aside from forces and moments, is there interest in cooling or brakes or some other specific elements? The test then proceeds as per the agreed plan.

As with any laboratory test, correlation is crucial and results should always be verified via some form of real-life track testing. It's usual for a wind tunnel correlation loop to have the following flow:

scale model in tunnel –> full-size car in tunnel. Full-size car in tunnel –> full-size car on track.

This is often why you see F1 teams during pre-season testing with elaborate aerodynamic rake assemblies featuring Kiel probes and other such devices. They don't have the luxury of full-size wind tunnel testing, so must go straight from scale model (usually 60 per cent) to track verification.

CFD advances

CFD methods have advanced so much in recent years that one may wonder if there will be a point at which wind tunnel testing becomes obsolete. ORECA is an example of a motorsport organisation that abandoned wind tunnel testing just over a decade ago, and has found success in the approach and methodology they developed to replace it.

'We are among [a limited number of] organisations, if not maybe even the only one, to operate at this level using only CFD. As technology develops and cost is squeezed more and more, complex wind tunnel test programmes look less attractive and cost efficient,' David Floury, technical director at ORECA says as he reflects on the choice.

'It is an endless process to improve the methodology and correlation with the track, but a wind tunnel is also a different picture of the truth and needs a lot of energy to ensure good correlation. We have reached a level we are happy with, but we keep on improving.'

Many teams don't have their own wind tunnel facilities and are therefore forced to outsource their requirements to test suppliers. Aside from the cost, this can sometimes bring issues with test slot availability, and sometimes having quite rigid gateways in the timeline doesn't work for programmes where more flexibility is required. Combined with regulations strictly limiting their use in some of the more high-profile championships, perhaps we can expect more teams to follow ORECA's lead in the future?

This CFD-only approach requires quite a substantial modification to the usual design structure and overall project timeline, but clearly has benefits if it can be made a legitimate alternative.

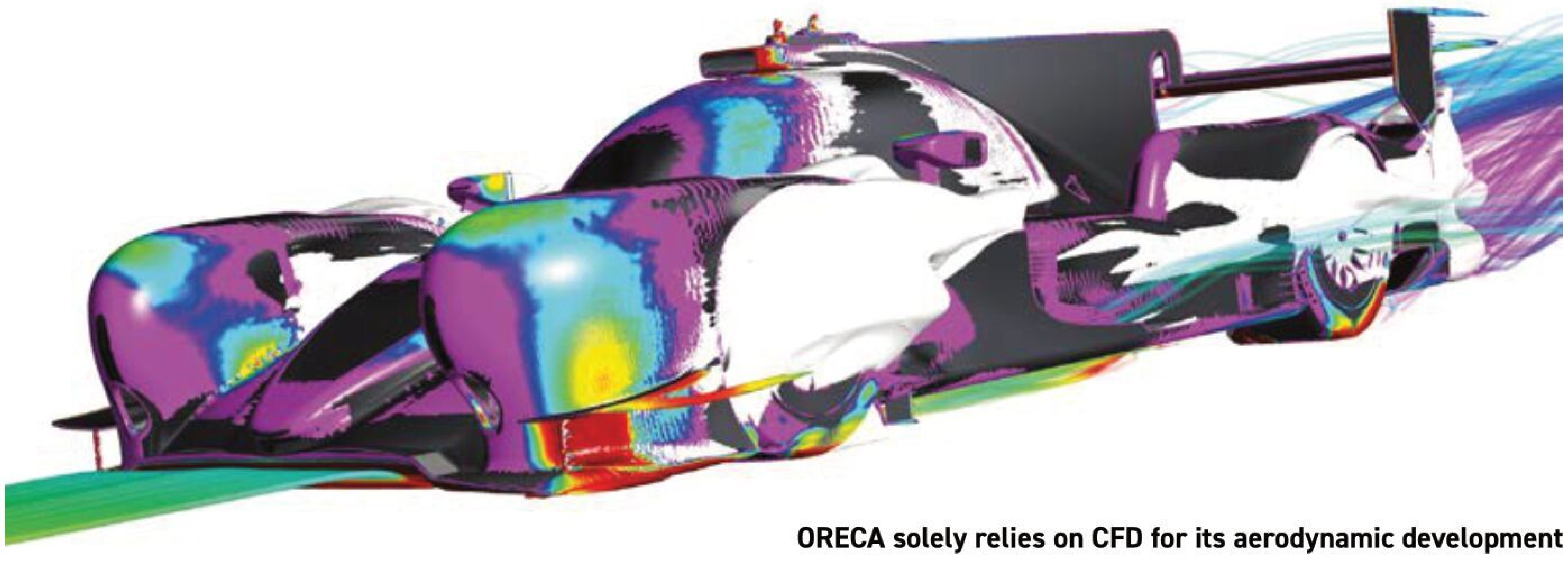
'We decided a number of years ago to develop and invest in our in-house CFD resource, developing our own methodology and correlation processes. It proved to work quite well so we continued to develop it, and we've also been able to use this in different areas of business, which is nice,' adds Floury.

It's still swings and roundabouts as CFD solutions still do take significant processing time, though that is speeding up all the time. The benefit of having an accurate model motion system controlled in real time is it allows a huge amount of data to be gathered in a short run of 10-15 minutes in a way that CFD can't quite match. Yet, with the ability to also take measurements during the transient phase of any model movement, physical testing provides a great advantage in terms of time and information gathering.

Operations such as TGR, who have the privilege of custom built, dedicated facilities and a full in-house operation from blank design to race day certainly stand by wind tunnels for the immediate future.

Artes Max

As often seen in Barcelona, all manner of measurement apparatus appear in efforts to correlate lab and CFD methods



ORECA

ORECA solely relies on CFD for its aerodynamic development


180 MPH WITHOUT MOVING AN INCH

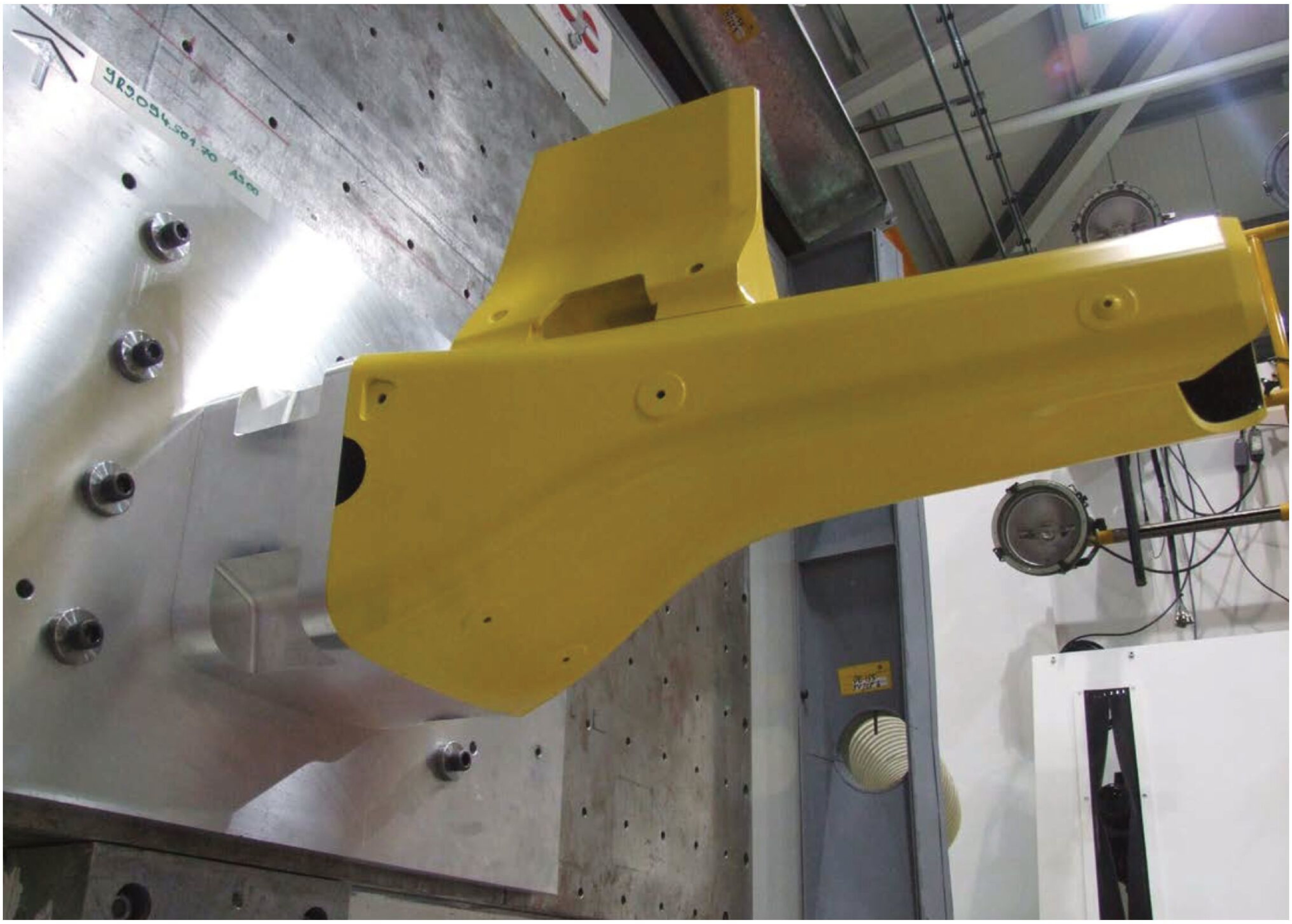
First impressions

Cranfield Impact Centre plays a crucial role in ensuring the safety of racecars. With tougher regulations coming into force in 2021, *Racecar Engineering* investigates

By Andrew Cotton

Racecar and driver safety has come a long way since the 1983 FIA regulations required the introduction of an additional box structure into the nosecones of Formula 1 cars

» FIA-approved crash testing facilities have been created in order to conduct repeatable, measurable tests



Crash test speed was 10m/s in 1985, but in 2021 will increase again from the current 15m/s to 17m/s. That equates to an almost 50 per cent increase in energy absorption

Hearing the news that a car has passed its crash test is now commonplace in racing circles. As advances in computer software through the design phase improves, so does the ability to predict how one will deform, but it was not always the case. Racecars from all series have often failed their first impact tests before heading to the track, particularly as rules tightened at key moments and design teams had to react quickly, perhaps with the risk of losing performance.

Long gone are the days when crash testing meant dropping a car, or component, from a crane into the ground to estimate the likelihood of a driver surviving the impact. Also behind us are the days when racecars would not even be tested, extra material only being added in order to improve performance, rather than driver safety.

Today's crash test criteria are stringent and the results are clear to see. Advances in composite materials, accident investigation and computer design have all helped create regulations that have yielded some of the safest racecars ever produced.

Yet, in order to approve car design before the cars hit the track, a component, or car, needs to be properly evaluated. And for that to happen, FIA-approved crash testing facilities have been created in order to conduct repeatable, measurable tests. One of these is housed on the campus at Cranfield University in the UK, and it is not unusual to have Formula 1 and WEC cars pass through the doors to reach certification for racing.

When we visited the facility, essentially a hangar in which all the test and measuring equipment is housed, there were a range of vehicles that either have been tested, or are about to be, including a Dakar tube-frame chassis and, sitting next to that, a wheelchair. In a box next to the wheelchair are bolts which hold Formula 1's Halo device in place.

This is not just a racecar test facility, and those running the tests are not necessarily racing fans. Their sole goal is to establish if a vehicle, or component, is fit for purpose, and they have been doing that for 40 years.

Primary function

In order to understand the challenge that the crash testing process poses, a design team must create a monocoque, or tub, from which the component parts of the racecar are hung. These include the front crash structure, side impact protection as well as functional items such as the front suspension and side radiators. However, the tub's primary function is to be the survival cell for the driver in the event of an accident, one in which the body will be as protected as possible.

From the roll hoop above the driver's head to the bottom of the tub, normally sculpted for aerodynamic efficiency, the structures have to withstand enormous pressure in a combination of both dynamic and static tests to prove not only strength, but also the correct deformability for a given part.

Williams' FW10 was the company's first carbon tub car but the composites team was unsure whether or not it would pass the crash testing criteria so came up with a back up plan of a honeycomb structure in the nose

The former essentially establishes deformity in the event of an accident, the latter ensures the parts are fitted well enough that they don't simply fall off at a measured minimum impact speed.

The combination has produced cars that are capable of withstanding impacts that previously may have led to injury or death of a driver, but there is more to the tests than simply crashing a component, car or wheelchair into a solid wall. In order to prove the parts are able to withstand impact, each test must be measurable, repeatable and accurate. Data gathered must then be shared with the design team and governing body to confirm the car is safe before it is put into production, or allowed to race.

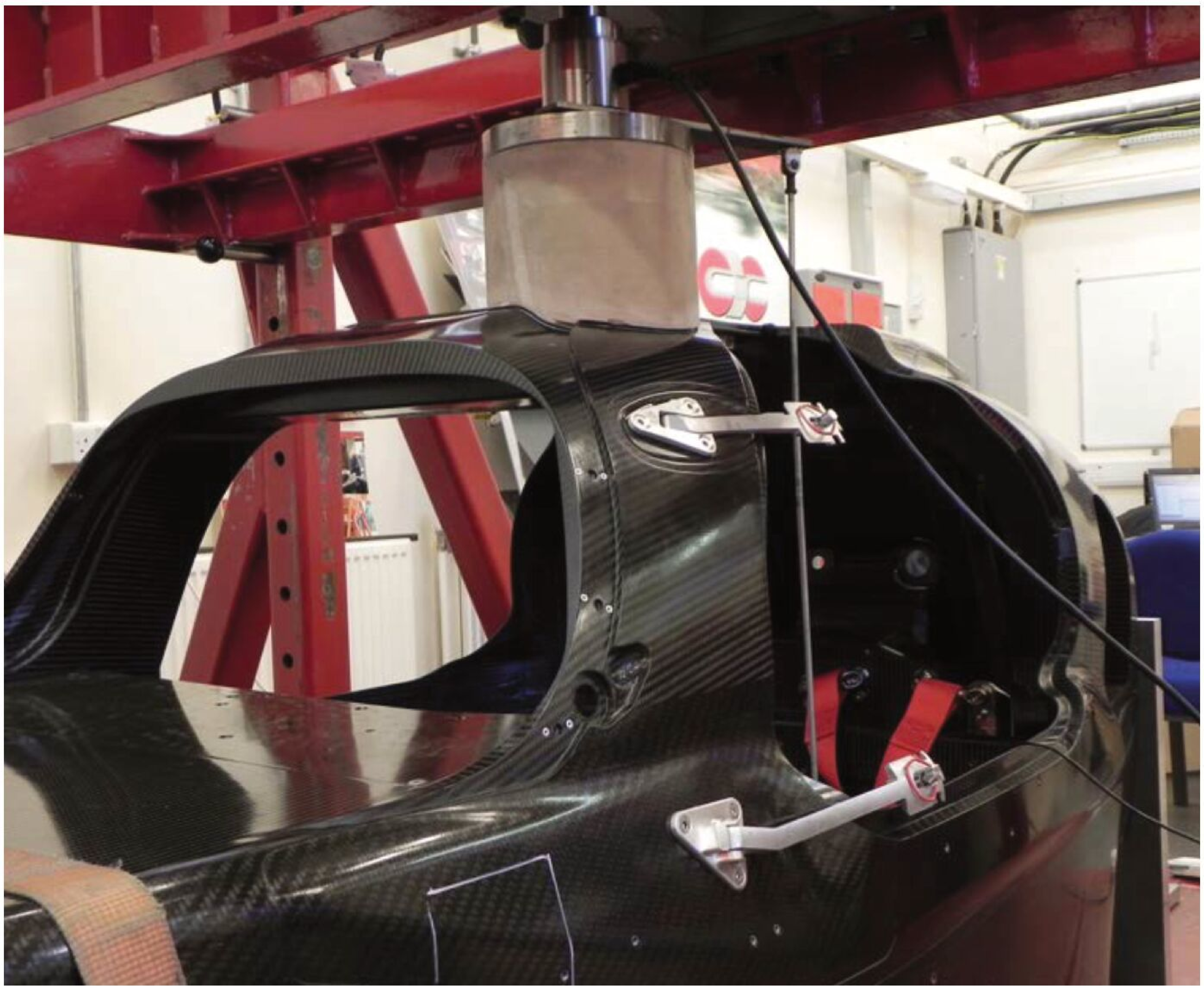
In order to do that, not only must the equipment be maintained to the highest level but the latest technologies need to be incorporated, including high-definition cameras, accelerometers and computer software. The results must be fully understood too, in order to provide meaningful reports back to the involved parties.

History repeating

The history of crash testing at Cranfield stretches back to the mid-1980s. Prior to that, teams would generally only strengthen their cars to increase torsional rigidity for the purpose of improved performance. Lotus and McLaren brought carbon chassis to Formula 1 in the early 1980s and, although the structures were stronger, and protected the driver better, it was not necessarily for that purpose carbon tubs were introduced.

Lighter and stiffer, the cars were going to be faster than their aluminium-bodied competitors and, as such, had a performance advantage. However, back then there was less knowledge of how to lay up the carbon fibres for strength and specialists were needed to ensure the finished racecar was as strong, or stronger, than an aluminium one.

Even then, actually testing the car for strength was not a priority. 'There was a regulation change in 1983 where we had to add a bit of extra box section on the front,

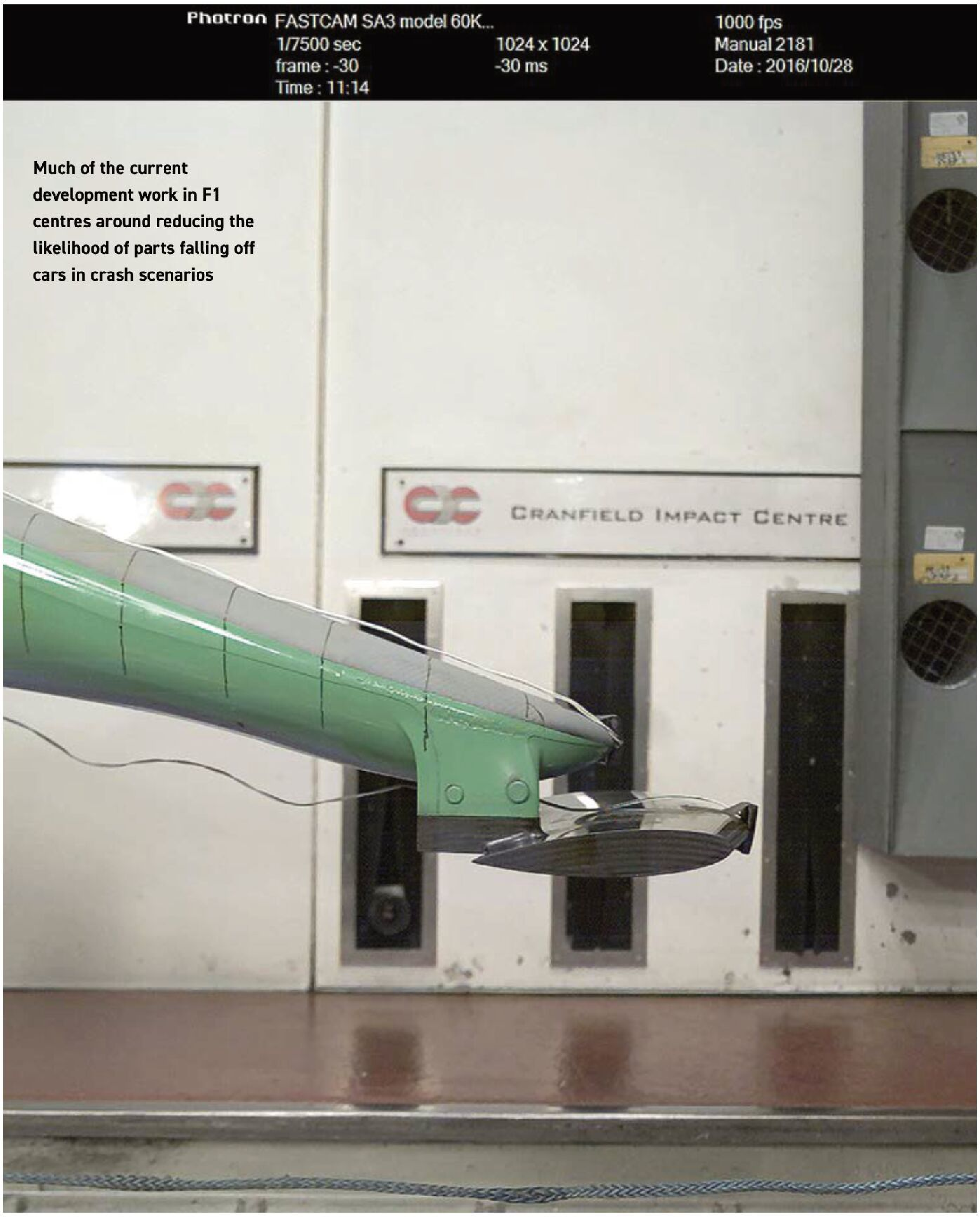


There is a misconception that static tests are easier to pass than dynamic, but withstanding pressure is a challenge

» There is more to the tests than simply crashing a component, car or wheelchair into a solid wall


400
300
200
300
200
100
100

The latest high-definition cameras record tests and results can be sent digitally in real time if required



Much of the current development work in F1 centres around reducing the likelihood of parts falling off cars in crash scenarios

which I remember was a bit optimistic,' recalls Brian O'Rourke, former chief composites engineer at Williams Grand Prix Engineering. 'Those things were not very substantial.'

The calculation at the time was that an average human being could survive an impact of around 20*g*, or 20 times their own bodyweight. Due to the fitness levels of professional racing drivers, the limit was raised to 25*g* for the purpose of testing.

'It was very rudimentary, but they came up with an energy level that equated to a speed of 10m/s, and that was intended for the start of the 1985 season,' says O'Rourke.

Pendulum swing

At that time, IndyCar had already started testing its chassis for high-impact accidents, particularly against the walls that line an oval track, and Formula 1, which typically sees lower-speed accidents, was right behind.

The process used in the first crash tests involved a pendulum rig. A block was strapped to it and swung into a the test object at the required speed. Originally, Cranfield's rig was designed to test railway carriages so, for the purpose of testing Formula 1 cars, it was well within its tolerances.

For O'Rourke, who was preparing the Williams FW10 for the 1985 season, this was just the latest in a series of obstacles that had to be overcome for the design team. The FW10 was Williams' first carbon monocoque and the opening round was in Brazil early in April. Because of the time it took to ship a car, the crash test had to be completed early and the team was not at all sure it would pass the required test. So a back-up plan was devised, a honeycomb structure in the nose that could be attached to the FW09.

'I had already done the thumb calculations on it and said to myself that there was no way this was ever going to do the job,' remembers O'Rourke. 'I don't think these guys had any idea of how far adrift the cars of that time were, so the only way to achieve this was to put a big honeycomb structure on the inside of a standard nosebox.' The first test was done at half speed and, while it stood up to the impact with only 50 per cent deformation, at full speed the nose collapsed so fast that the rig broke. 'I had taken bin liners to bring the parts back, but there was nothing left to recover,' says O'Rourke.

After a long lunch, taken while the rig was repaired, they tried again with the honeycomb structure and this time it passed. 'It was a reasonable absorption curve, so that was the starting point. Actually, I had made it a bit too stiff, so what happened then was that it pushed the front of the bulkhead into the monocoque, which wasn't intended.

'We had a bit of a re-think about beefing up the monocoque and went back a week later. We managed to pass that one.'

This may have been the early days of crash testing, but the same issues have arisen ever since. Above the door to the Cranfield test rig today is a Formula 3 chassis that had been subjected to the side impact tests mandated by the FIA recently. The holes in the side of the monocoque indicate it suffered the same issue as Williams nearly 40 years earlier.

With such pressure on teams to produce cars capable of passing the crash test before being certified to race, there is a clear loophole that, according to folklore, was often exploited: building one car specifically to pass the test, but not the same specification as the car on track. This was a clear area of danger that had to be addressed.

When Formula 1 went to high noses with the front wing hung from the underside on

» Structures have to withstand enormous pressure in a combination of both dynamic and static tests

It is not just racecars tested at Cranfield Impact Centre, all forms of technology come under similar scrutiny

pylons, these were not necessarily the same as those used in crash testing. 'There is a lovely story about an F1 team who aren't around any more, but who went to the first track test in Spain and the first time the car left the pits the front wing fell off,' says O'Rourke. 'It was the one intended for the crash test, not for track running.'

Martin Donnelly's accident at Jerez in 1990 led the FIA to change crash testing protocols, too. While the monocoque had passed the test, there was a clear failure in the chassis, which split in two during impact.

'From 1991 onwards, you did all of your tests on a data chassis, and every other chassis had to go through five squeeze tests as today, so you have to show that every monocoque you build will not deflect more than the original one,' explains O'Rourke.

Another test that was introduced following the 1991 season was on the roll hoop, which required the highest structural part of the racecar to withstand a pressure of seven tonnes. It was one of the biggest changes in safety regulations and, while designers focussed on lowering the c of g by using composite materials, when the regulations became even more stringent in 2001 they were forced to go back to metallic inserts within the composite structure in order to meet the strength required.

More recently, additive manufacturing has allowed for a titanium roll hoop to be fitted and that is what is used in today's F1 cars.

'Today's ones look very much like they used to in the 1970s,' says O'Rourke. 'If you get down to it, metallic structures are back in, but there has been a lot of heartache and lost sleep since then over passing these tests.'

The big squeeze

From testing the front of the car, the FIA then moved to testing the monocoque with a combination of squeeze tests and dynamic tests. Both are still used on racecars today, though now they have to withstand greater levels of pressure and impact than ever before, and passing the test is about to become even more difficult.

The FIA is soon to release a new set of criteria for the test houses to adopt, and Cranfield Impact Centre has been directly involved in its development.

'This goes further on all technical aspects,' confirms James Watson, Cranfield Impact Centre manager. 'What specific regulation crash test is needed? Is the instrumentation fully calibrated? Is it traceable? Can you record it repeatedly when you measure the acceleration? What range of uncertainty is your measurement?

'There is a regulated method that the whole test should be documented and approved. When you take any crash test it is impossible to perform exactly the same crash test twice. You could say the friction might change, or the humidity or temperature, and controlling those is what makes sure the test is repeatable. That's what the purpose of the thorough preparation is.'

Under the new regulations, Formula 1 crash testing will move to a faster crash test speed, up from 15m/s to 17m/s, with a slightly increased mass. 'The speed increase doesn't sound like very much, but the energy will go up from 88kJ to 130kJ, because it is $1/2mv^2$. Any increase in velocity is a massive increase in energy,' notes Watson. 'Therefore the energy absorbing capabilities of the vehicles will be significantly improved.'

Having accurate measurements is one thing, but the data analysis afterwards is also critical. 'The nose cone, for example, has to pass different criteria to absorb the energy within the first 60kJ,' explains Watson. 'We then perform the analysis demanded by the FIA, which is unique. For example, you have to make sure the nose cone doesn't come off after a glancing blow before the car goes into a solid wall. So they put a large force into the side, 40kN, and hold that for 30 seconds.

High in fibre

Bcomp and YCOM have collaborated to develop and manufacture the world's first natural fibre crash box for motorsport, the Front Impact Absorbing Structure (FIAS), using Bcomp's powerRibs and ampliTex material.

Designed by leading advanced technologies expert, YCOM, and using higher performance ampliTex flax fibres, it proves natural fibres can play an important role in structural and safety-critical parts.

The crash box is designed to optimise the performance of the ampliTex natural fibre reinforcements and was tested at the FIA-approved test house of Politecnico of Milan. The impact test results achieved were in line with a traditional carbon fibre structure. The material not only shows the desired crash behaviour required from a safety perspective, it eradicates the danger of sharp splintering. Furthermore, natural fibre composites waste can be used for thermal energy recovery.

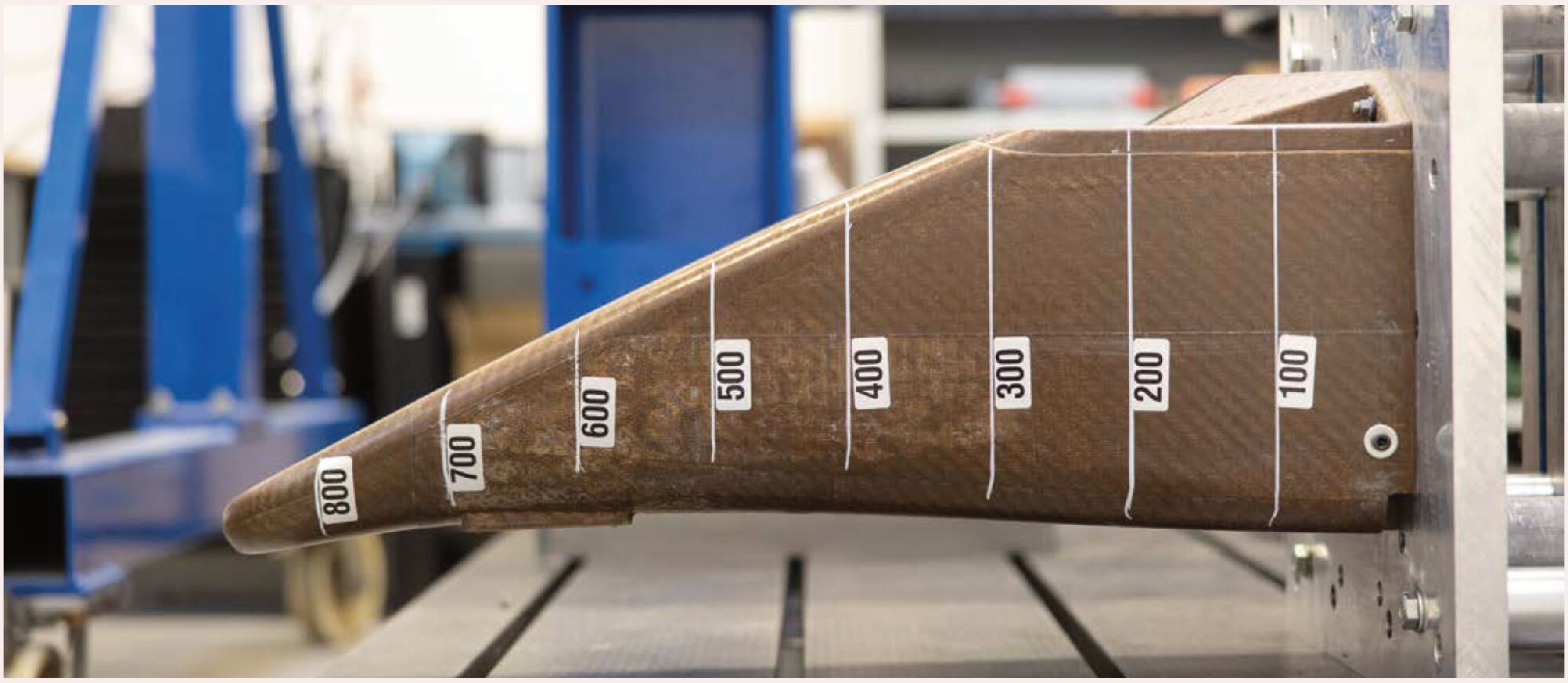
For the motorsports industry, this new research proves high performance natural fibres can be used for significantly wider applications than previously thought, reducing environmental impact and enabling technology transfer to mobility.

The natural fibre FIAS prototype designed as a proof of concept is currently around 40 per cent heavier than its carbon fibre counterpart, but enables a CO_2 reduction of approximately 50 per cent in the production process compared to the composite piece.

Pushing the adoption of natural fibres requires engineers to integrate it from the first day of the design phase,' says Mario Saccone, YCOM co-founder. 'Mastering the full process is the only way to optimise performance and increase the competitiveness of sustainable composite materials.

'We are really happy to collaborate with Bcomp in this development. Motorsport is a forge for new technology development, but this must be done fast and without any risk of error. YCOM has the experience to embark on complex R&D projects, with the flexibility of the motorsport approach to accelerate development.'

» Under the new regulations, Formula 1 crash testing will move to a faster crash test speed, up from 15m/s to 17m/s, with a slightly increased mass



Still only at the development stage, the ampliTex flax fibre nosecone carries a significant weight disadvantage over carbon fibre, but a 50 per cent reduction in the CO_2 used in its production

However, with early crash test results on a par with those achieved with the carbon part, it is surely only a matter of time before that weight penalty is eliminated by racecar engineers

That's a serious test, but it stops the nose cones falling off in the initial stages of a crash.'

Another key area of ongoing development is the seat. 'There used to be two levels of seat – advanced rally seat and competition seat,' says Watson. 'The rally seat has been in for 10 years now and is up for renewal. They are doing a static test for that. The competition seat was a dynamic test but now they are making both static tests. There are going to be more seats being tested.

'There is a misconception that the dynamic test is harder to pass but, if you look at accident data, the forces seen in a crash occur over a very short space of time. If that same force is applied for 30 seconds, it is much more significant.'

A further big change coming to racing in the short-to-medium term is alternative fuel technology. In particular, highly-pressurised hydrogen fuel cells. These will require a whole new way of testing, but Watson is not concerned as he runs a facility that caters for all walks of engineering, not only racing.

Safety service

'As long as it is safe, it will absorb the energy,' he says. 'That's the service we are providing. We are not dictating what the regulations are, or what we test. That comes from the FIA or relevant governing body. The engineering side is more interesting to me, and it really could be anything, from ambulance components to wheelchairs. It's the mechanics of it, and making sure we are providing a good test service.'

The ability to deliver the information has changed in 2020, thanks to the coronavirus pandemic. Before, testing would be witnessed by the team, Cranfield staff and officials from the relevant governing body. But with social distancing now a requirement, it has become a more remote process, with the high-speed camera footage, test results and analysis all sent back to headquarters digitally. If anything, this has improved the process at Cranfield, with fewer people on site.

'People are able to view the tests much closer via a tablet or Smartphone, so that has opened up a whole new way of working,' says Watson. 'It has reduced the number of people travelling to witness the tests.'

While the test facility at Cranfield has updated its working practices to cope with the pandemic, with the ever more stringent tests ahead for the next generation of Formula 1 cars, the Impact Centre has also upgraded its facilities to meet them. The drive for safer racecars continues.

Revolution sounds like a whisper

You cannot hear them, or feel them, but the advances in motorsport keep on coming

The Abu Dhabi Grand Prix that finished the 2020 Formula 1 season was not a remarkable race. It was an exercise in tyre management that produced minimal drama. However, a key talking point emerged from the event, and that was the pre-race demonstration by Fernando Alonso of the 2005 title-winning Renault. Powered by a V10 engine, it set hearts racing with its assault on the eyes and ears of those watching. Although it looked and sounded wonderful, it was slower than the cars that took the start of the Grand Prix by some seconds, despite being lighter, but the way the car moved around in the corners as the driver struggled to deliver the power through the rear tyres was both testament to the high downforce levels of the modern design age and the efficiency of the modern racing power units.

Audi's former head of powertrain, Ulrich Baretzky, said that glorious sound was wasted energy as he developed the diesel engine for the Le Mans programme, among his many projects. Now, the power units (internal combustion engine plus hybrid) have a thermal efficiency of more than 50 per cent, meaning they turn more than half of their generated power into energy delivered at the wheels. This is an extraordinary figure, one that should be widely celebrated by the engineering and wider community, yet it is largely ignored by the media as it is not that interesting to the general public.

Overall lap time is considered the most important factor in modern Formula 1, and the most recent iteration of racecars has decimated pretty much all the existing lap records. The cars don't *look* fast, don't *sound* fast, but are quicker than anything the category has ever produced.

Efficiency drive

Motor racing is all about efficiency. The less cooling required by a power unit, the better the aerodynamics and overall packaging. The more power is turned into used energy, the faster the car will go. The less fuel a car uses, the lighter it can start a race. The better it can use its tyres, the more strategy options are open to the race engineers that can positively affect the outcome of a race.

The hybrid era of Formula 1 started under the presidency and direction of Max Mosley, who identified the need for electric propulsion to be critical for manufacturer involvement in motor racing. That has been further backed up by more recent FIA studies that show it remains an important part of their sales pitches to the board of management as they seek to use motorsport to drive forward their knowledge of future propulsion technologies. Yet the lack of sound from the engine, coupled with the increase in downforce and more efficient aerodynamics, has led to cars that, while fast, are not as interesting to watch for the spectators at the track. Alonso's lap in Abu Dhabi only served to highlight that fact.

> » The next generation of racecar designer will have to balance more risks than they do now

The quest for both aerodynamic and power unit efficiency has seen a huge escalation in design potential. A modern Formula 1 team can have more than 1000 employees working on the two prototype cars that turn out on around 20 weekends of the year. The detail into which they are able to delve in order to perfect the design is incredible. The problem is their Holy Grail is, as it always has been, lap time, not excitement.

A demonstration lap by Fernando Alonso for Renault set hearts racing, but was it wasted effort?

Formula 1 will introduce a budget cap that will directly affect the size of the teams, and that in turn will limit the amount of detail into which a team can go during the design and development phases of a racecar. From an engineering perspective this is not ideal, but what it might do is lead to bigger risks being taken by the design team. If a design is not certain to succeed, would you consider running it on your car? If it gives more performance then the answer is yes, but how will you know? Testing is to be limited too, while Formula 1 is looking to introduce more races to the calendar, which will further restrict development time and opportunity.

The squeeze on resources will increase further still as the budget reduces, and so the next generation of racecar designer will have to balance more risks than they do now.

The conundrum is not new. Formula 1, as with all areas of motor racing, is about extremes, and that includes pushing time limits, budgets and the very essence of human endeavour. New technology that speeds up design and development processes will be brought into the sport if the money is there to do so, which will present new opportunities. It will be interesting to see how motor racing adopts these technologies, while continuing to push the boundaries, and perhaps introduce a little bit of the old magic, without compromising the incredible advances that have been made in the modern prototype age.

Andrew Cotton


700
600
500
400
300