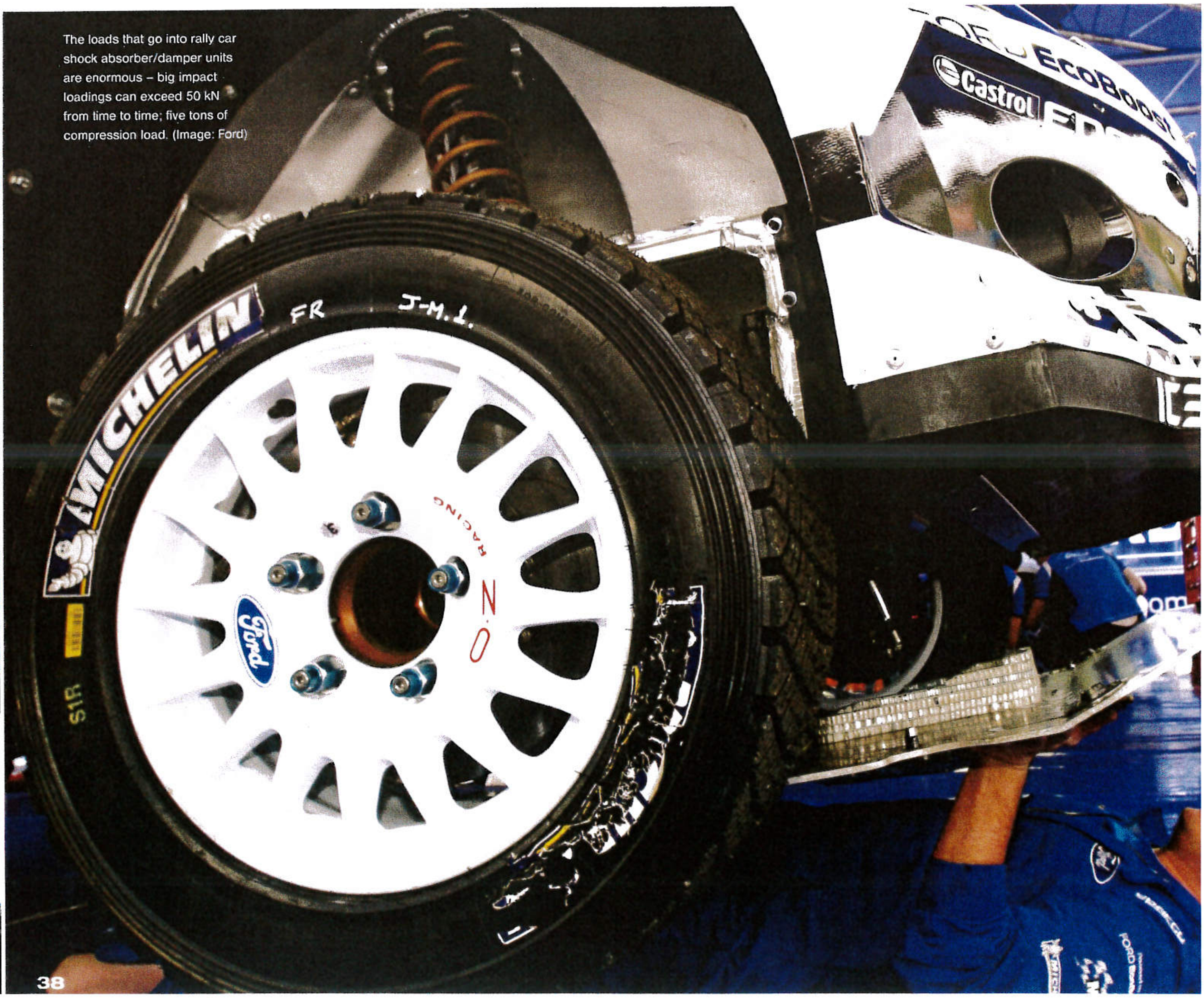
Suspended

Martin Sharp considers the wide and varied functions rallying suspension must perform, and how component designs have developed

Sub-zero snow and ice, smooth asphalt, broken-up asphalt, dirt surfaces of every kind, big rocks, smaller rocks, pebbles, gravel, deep puddles – you name it, the chassis of a rally car must be designed to be competitive and withstand a huge variety of surfaces, weather conditions and altitudes.

The complexity of the vehicle dynamics involved in rallying is immense, as highlighted on page 32. But how are the key chassis components of a rally car that interact with this worldwide range of different surfaces arranged and designed? They are components and assemblies that must be able to cope with massive shock loadings



The loads that go into rally car shock absorber/damper units are enormous – big impact loadings can exceed 50 kN from time to time; five tons of compression load. (Image: Ford)

animation

from many directions while providing the car with competitive levels of grip for accelerating, braking and cornering.

As in most motorsport design disciplines, rally car chassis components are subject to levels of compromise – they have to provide precision, ruggedness and specific durability while being capable of accommodating and performing under very big loads. They must also comply with the particular regulations applying to the branch of rallying for which the vehicle is designed. Cross-country rally (or rally-raid) regulations, for example, apply vertical wheel travel restrictions – 300 mm for 'live' axles and 250 mm for other suspension types – while in the WRC there is no specific wheel travel restriction in the rules. Generally though, throughout rallying there are restrictions on anti-roll bar types and materials, bans on active or electronic control of shock absorbers, and any connection between dampers and/or front and rear anti-roll bars and so on is outlawed.

Shock absorbing, damping and tyres

Motorsport engineers tend to prefer the term 'damper' to 'shock absorber', but in rallying that is only partly accurate because many of the characteristics of a rally car damper are dictated by the need to absorb bumps, jumps and shock loads, which is part of its job. In a purist way it is perhaps correct to use the word 'damper', but shock absorbing is a big part of the job for a rally car unit, which has characteristics as much driven by its role as a shock absorber as by its role as a damper.

On a Formula One car for instance the damper role is nearly everything, driving the unit's characteristics; while on a rally car the damper's role as a shock absorber is equally important.

The damping and shock absorbing roles are quite different. When a rally car lands after a big jump the energy must be absorbed; the spring alone cannot do that, and if it did the car would bounce back up in the air, so it's the shock absorber that absorbs most of the energy of the big inputs the car sees, and it gets a lot of them on a rally.

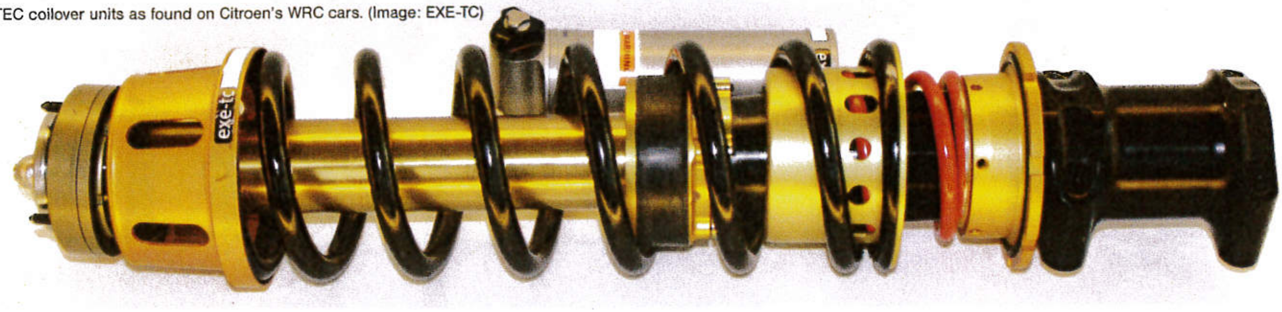
The loads that go into rally car shock absorber/damper units are enormous – big impact loadings can exceed 50 kN from time to time; five tons of compression load. These days strokes in excess of 300 mm are used, and velocities of more than 4 m/s are seen regularly.

These are huge numbers compared to a roadcar, and it is these that drive the mechanical design of rally car dampers. Largely through regulation, MacPherson struts tend to predominate in rally cars. As part of the suspension structure this strut unit must be capable of withstanding such large loads, particularly when they are bending loads from side impacts.

In the traditional MacPherson construction, which is used in many cars these days in the WRC, the damper takes some of those side loads, although some cars now run an inner and outer tube to take the bending loads with the damper sitting inside simply to contribute to absorbing and restraining vertical loadings. This is legal because it's still in the MacPherson unit and still performing the same function.

In terms of jumps and damper speeds, the height provides an indication of the closing velocity to the ground, which gives the damper speed: a 1 m high jump will result in a damper speed of around 4 m/s. Also driving damper velocity is the stiffness and height of the tyre sidewall. Driving over something at high speed, the impact

EXE-TEC coilover units as found on Citroen's WRC cars. (Image: EXE-TC)



upright and then the damper.

The level of damping effect in a tyre is relatively small. It can be imagined as a spring, absorbing most of what you see on a gravel road. The role of the tyre is vastly underestimated, but it is the most important spring on the car and it is the damper that manages the effect of the tyre – the tyre does nearly all the work. Averaged over gravel and tarmac suspension arrangements, the typical response rate of a rally car's unsprung mass is about 10-15 Hz. A road speed of 100kph equates to around 28 m/s; so a maximum response rate of 15hz means that the suspension will not be able to handle all of the features encountered, thus the tyres must deal with these.

So when a rally car travels over a bump, the tyre absorbs it then the damper and spring deal with it – but it's the tyre that absorbs and soaks up all the rocks, stones and bumps in the road.

Damper architecture

There are plenty of hydraulic damper types around, but typically in rallying there's the classic old-style Bilstein-type competition damper, still in demand these days by certain historic rally championships – although, as an example, Ford Boreham's in-period failure to add a photograph of the Bilstein units to the original homologation papers of the Mk I and Mk II Escorts remains a matter of conjecture to this day!

Before Bilstein, the classic MacPherson had the piston rod (say 25 mm diameter in a roadcar) sticking out through the top of the strut and fixed to the top mount with the damper at the bottom of the strut, with bending loads directed to the top section of the casing. To take account of these loads, Bilstein turned this arrangement upside down, with the piston rod fixed to the bottom of the strut and the damper unit fixed to the top mount and sliding in the strut casing. So, instead of putting bending loads into a 25 mm piston rod they now go into a 50 mm top section of the casing, and the piston rod sees no bending loads.

Then, back in the mid-1990s (quite possibly first in Touring Cars) came a further step of an outer tube with an inner tube with linear or rolling element bearings which are not actually part of the damper. This produces a sliding tubes within which it fits. There's the elegance of separating the damper from the bending loads, but the disadvantage of having three tubes instead of two. It is used in rallying, but more of the 'conventional' struts are still used today.

While damper manufacturers all have their own designs, in practice there are about three or four common damper types in modern rallying, although they don't differ much in the basic role they have to play. Essentially, the main piston and its rod must be accommodated in the damper. The rod must have a finite diameter so that, as it goes in and out of the damper, the available space for the fluid varies. Accommodating that change in volume for the fluid in the damper is almost invariably achieved in rallying with a gas spring – a separating piston and some pressurised gas.

To return to the classic Bilstein 'monotube', this has the separating piston and pressurised gas at the top of the unit, at a pressure that will accommodate the change in volumes of the oil as the piston goes up and down. This also reduces any possibilities of cavitation of the fluid. The remote canisters, or cylinders, that are common on modern rally dampers work on exactly the same principle, except that the gas/oil chamber is often at the end of a hose.

At Rally Finland in August 2012 Citroën Racing changed to siting the canisters physically on the bottom end of its gravel dampers, a solution that avoids the hassle of hoses and offers better adjuster accessibility, improved damper cooling and swifter spring changes. Ford/M-Sport has been using this arrangement since the Focus WRC.

Three way adjustable dampers as fitted to the current Mini WRC car. (Image: Martin Sharp)

External resevoirs are the norm on rally dampers, helping to reduce heat build up in the damper fluid. (Image: Reiger)

the FIA has prohibited their use in rallying in the interests of saving costs. Plain, sliding bearings must now be used. While the evident advantage of needles or balls is lower friction, a good sliding system these days can also be very low friction and, as such, they are probably not impairing the damping very much. The key issue here is that consistency is the most important thing, rather than the forces involved, and with rolling element bearings the friction levels are not just low, they are also very consistent.

At the clubman level of rally damper, an adjustable valve to control the flow of oil into the remote canister works only over the diameter of the piston, because the oil can still flow through the shim packs in the piston; good for small adjustments on the compression, together with a hollow piston rod containing a conical needle as the bleed for the rebound through the piston. This is essentially the first level of gas adjustable dampers.

After this simple first step adjustable dampers become more and more complex as engineers want high-speed and low-speed adjusters. Top rally dampers will have separately adjustable high- and low-speed compression adjusters, a rebound adjuster and, in the case of Reiger, a stability system for very low damper speeds.

Using shims to regulate the flow of fluid through pistons is pretty much universal in rally dampers. Mimicking the own-design dampers Peugeot uses in roadcars, Peugeot Sport used a similar high- and low-speed springs and balls valve arrangement in the 206 WRC before resorting to Öhlins units. However, using shims of varied thicknesses and diameters in a stack makes it easy to vary the force-velocity curve, and is a very flexible way of achieving good damper characteristics.

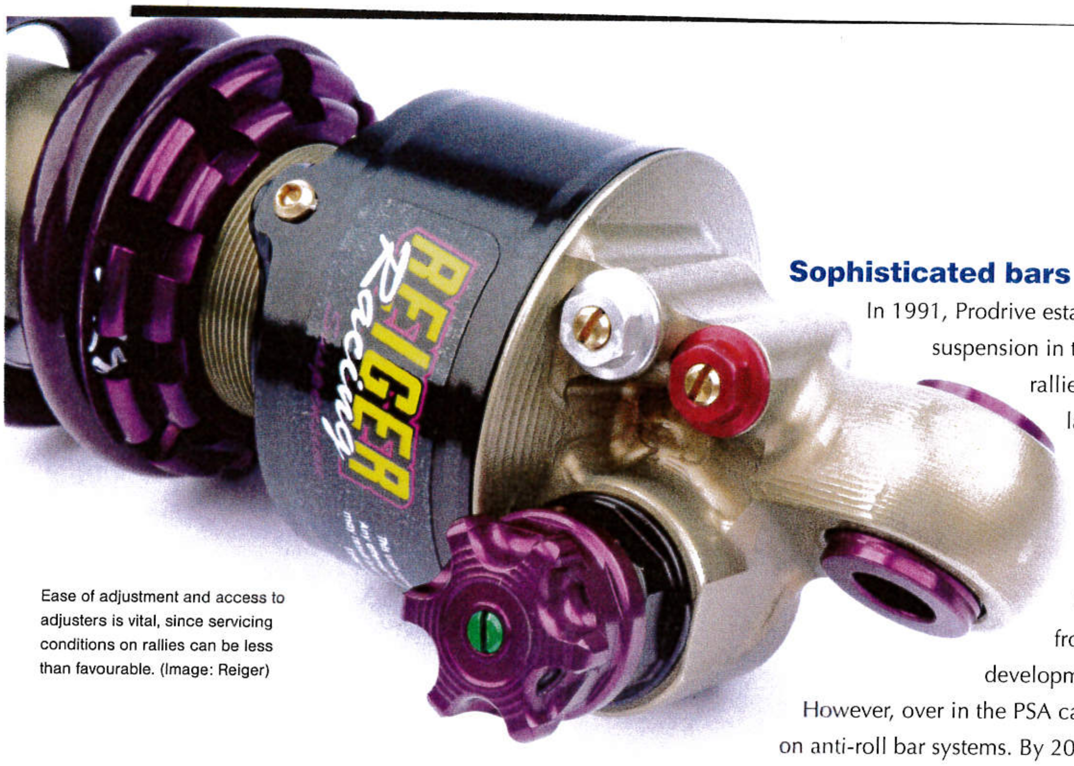
The multiple holes through the pistons – for rebound in one way and compression the other – are usually of complicated shapes, and oil flow through them is resisted by the shims, which deflect according to their stiffness, diameter and thickness; and number in a stack. In principle, the base force-velocity curve should be a straight line, which isn't what you get with just a hole or holes in the piston, so the shims are used to achieve the characteristics required. The starting point may be a linear curve, but tuning is 'horses for courses', and while racecar dampers may have progressive curves, rally dampers tend to have a softer bleed at the beginning for grip. Digressive curves – where the faster the velocity, the less swiftly the

Damper manufacturers and top teams work together closely on damper designs, and aim for an expectation of 500 km per unit before being 'wiped with an oily rag', then recommended service intervals are set at around 1000 km, although dampers have become pretty durable these days. Here it is perhaps relevant to note that some Dakar Rally trucks have achieved top ten finishes on one set of dampers without service.

Although WRC dampers have high- and low-speed adjusters for bump and rebound, they are only useful trimming tools and not substitutes for having the right damper in the first place, and the range of adjustment is deliberately not wide. Teams generally try to leave them alone, as they are fine-tuning devices. If they were to have a major effect then they would have to be a major part of the damper, and they're not.

When the piston hits the end of the tube it stops, so the damper restricts the stroke. A bump stop might be external to the unit while a rebound stop might be inside the damper. Indeed, during the 1980s and '90s, teams had less confidence in dampers and fitted rebound straps as well, which used to fail occasionally. Most rally cars these days though also have some kind of hydraulic bump stop feature as well as elastomer stops.

The effect of such hydraulic bump stop designs can be likened to that of the buffers at the end of a railway line: they are just to stop the damper punching through the bonnet/rear turret. These can be arranged over the last 50 mm of travel where something like a piston could be stuck on the end of the nut retaining the shim stack, and at the top of the damper cylinder – or the bottom if it's the other way around – there's a volume to accommodate the aforementioned 'piston'. Approaching full bump, the piston goes into that volume and traps some oil in there; then there could be shims, small holes or even tapered sides to produce an hydraulic bump stop that assists/works in parallel with the elastomer bump stop. When landing from



Ease of adjustment and access to adjusters is vital, since servicing conditions on rallies can be less than favourable. (Image: Reiger)

Sophisticated bars

In 1991, Prodrive established a small team to assess reactive suspension in the Group A Subaru Legacy, which never rallied with such concepts, although the later Impreza did. The Subaru was not to appear on a rally with what could be accurately described as an 'active' system until Sanremo 2003, in Petter Solberg's Impreza World Rally Car. But such systems were to be banned from the end of 2004, so the incentive for development was limited.

However, over in the PSA camp, developments continued apace on anti-roll bar systems. By 2003, Peugeot Sport had spent some two years developing its own electro-hydraulically controlled active anti-roll bar system for the 206 WRC, but this was dropped when inconsistent reactions restricted its use to smooth tarmac rallies. Again such systems were later prohibited.

Yet in the Citroën Sport branch of PSA its renowned rally engineer Jean-Claude Vaucard had developed an hydraulically linked passive anti-roll bar system for the Xsara WRC. The system first competed in the Monte Carlo Rally in 2003; thus equipped, the Xsara won.

Admirable in concept, execution – and results – this system provided an elegant and particularly neat solution to improving the suspension performance of a World Rally Car, approaching closely a 'gain without pain' zenith. Its operation patented and developed by Kinetic of Dunsborough, Western Australia, the system Vaucard chose to adapt for the Xsara WRC is what Kinetic calls its Reverse Function Stabiliser (RFS) system. Motorsport engineer Ray Munday worked closely with Vaucard for some 18 months to adapt the RFS to the Xsara.

The system exploits a principle that Kinetic describes as 'mode decoupling'. Conventional anti-roll bars cannot differentiate between a true roll mode and an articulation mode (or a single-wheel mode, which is actually a special case of articulation). So they continue to provide vertical stiffness to the wheels during articulation inputs, which is precisely when such stiffness is detrimental to suspension efficiency – and reliability.

The RFS system, however, can distinguish – or 'mode decouple' – roll input from articulation input. In practical terms this means that, when cornering, the RFS allows the anti-roll bars to react to roll forces exactly like conventional bars but, most important, if the wheel then also encounters a bump during the corner, the system distributes this additional 'bump force' across all four wheels, ensuring that the bump has minimal disruption to the vertical tyre force of the 'bumped' wheel. This happens simultaneously and instantaneously with no computers, pumps, valves or corresponding power drain.

On most rallies, using conventional anti-roll bars, wheel articulation is affected – to varying levels – by this torsionally induced inhibition from the bars most of the time. This compromises grip. It is the rally chassis engineer's job to try to optimise grip at each wheel through

Spring time

Progressive rates springs are beneficial in rallying. Apart from on the rear ends of some historic rally cars the spring type used is generally coil, but individual coil springs with progressive rates are rare. Spring combinations per corner are not illegal in most branches of rally sport, and most teams these days opt for the combination of two or more springs to provide a progressive spring rate.

This route offers flexibility and is cheaper. Most teams opt for a main spring and a helper spring, which work together to equate to a dual-rate spring – a quite soft initial area, then that first spring will go coil-bound and then the main spring comes in to provide the stiffer rate.

The corollary is one-off progressive springs, but these are expensive to make and are just one spring with fixed rates. Using helper springs, a team can come up with a basic range of three main springs and three helper springs for asphalt, and three different mains and helpers for gravel, in principle making nine different settings and rates per surface from six springs. These provide a very close approximation to that possible with single progressive springs – at less than half the cost.

There is a relationship between the softness of the spring and grip – the softer the spring, the greater the grip – but it is not linear. There are definite disadvantages to going softer with the springs and thinking that more grip will be available, but generally speaking softer springs mean more grip. Yet just as dampers have more than one role, so do springs.

Rally cars must go around corners, accelerate and brake, and the spring must also help control the body movement. Softening the spring increases body roll and pitch under acceleration and braking, which can be bad for grip; another compromise engineers must decide about and cater for. Additionally, for the driver, a car with reduced spring rates is less responsive, rolls more and takes longer to do it. Put simply, to achieve grip an engineer would run very soft springs, but the car would not go around corners very well.

Typical rallying spring rates for rally cars are 20-40 N/mm for gravel for 99% of the WRC field, while tarmac rates are around 50-70N/mm for asphalt, which is less easy, a greater compromise that creates ground more often and strongly, thereby improving grip and, potentially, stage times. More equal, and reduced, tyre wear is a further benefit.

The system operated passively to provide essentially uninhibited articulation of each wheel on the Xsara WRC. At the same time, roll stiffness was achieved independently and passively through the comparatively simple expedient (part of the elegance of the concept) of splitting each axle roll bar with double-acting hydraulic piston-cylinder assemblies. Each side of each piston-cylinder assembly is linked hydraulically, via a pressure-maintaining piston-type accumulator, to the side of the cylinder on the other axle, which is linked mechanically to the corresponding side of its split roll bar.

Let's say the Xsara WRC was going through a smooth left-hand corner with both right-hand wheels under compression roll forces: no fluid is flowing in the system and the anti-roll bars are working 'conventionally'. Now, suppose the right-hand front wheel hits a rock. Because the right-hand rear wheel did not experience the 'rock force,' the RFS 'knows intuitively' that the rock force cannot be part of the 'roll force'. This force 'difference' between the right-hand front and the right-hand rear wheels (effectively the rock force) obliges fluid to flow between the front and rear RFS cylinder assemblies.

In a conventional system, the rock force would be resisted by the front anti-roll bar, resulting in a massive vertical tyre load variation of the right front wheel. However, when the fluid flowed in the system fitted to the Xsara WRC, because both front and rear cylinder assemblies were double-acting, the flow was reciprocal (the amount of fluid going towards the rear in one circuit was matched by the amount of fluid flowing forward in the other circuit). The rear piston-cylinder assembly must therefore move to match the movement of that in the front cylinder.

The rear piston-cylinder assembly movement applied equal and opposite torque to the rear anti-roll bar halves to that received by the front bars. In our example, the result would be that the front right 'single wheel' rock force becomes a distributed four-wheel articulation force. And while all this is happening the system is maintaining the original roll force. Kinetic describes this last feature as 'Force Superimposition'.

Clearly in a roll situation the outside wheels must take more vertical force. So, taking our single wheel hit example, it is more accurate to say that the RFS system attempts to instantaneously 'position' the chassis to achieve the best available equalisation of wheel loading within the constraints of physics. More simply, it optimises wheel loadings.

World Rally Cars tend to be marginally nose-heavy. Taking the example of the right-hand front wheel hitting a rock in a left-hander, on hitting the rock the right-front wheel articulates, and fluid flow through the system resulting from that initial rock force also articulates the left-rear wheel, creating increased vertical forces on the left-front and right-rear wheels. So, in our left-hand corner, the – important – right-rear wheel is made to work a little harder for an instant.

The force transfers are practically

2003, potential and actual wheelspin and corresponding tyre attrition at the least loaded wheels was sensed and adapted to by the differential control mechanism. By optimising wheel loads all the time, Citroën Sport's simple yet elegant anti-roll bar system helped contain this.

Now though, connected roll bars are illegal. However, recent innovations come close to replicating such advantages. One company, for example, has patented a corner control valve system which detects whether the car is on a straight or a corner. In a corner the outer dampers stiffen to produce less roll – meaning softer anti-roll bars; hence more traction. The same company also has a rebound control valve that can detect whether a wheel is on the ground: if it is not then the system reduces rebound damping to slap the wheel back on the ground quickly to get traction. These dampers also incorporate a unique thermostatic device configured to compensate for oil viscosity change between warm and cold dampers, thereby maintaining consistent damping irrespective of temperature.

Public bars

Independent wheels with soft suspension and long travel are needed for grip, but then it's probably preferable for the car not to pitch or squat under acceleration and braking, and stiff anti-roll bars are needed to control roll in corners. Under the current rallying rules, connected anti-roll bars are outlawed, so with just springs, dampers and roll bars there's more compromise involved than with the 'different compromise' introduced by the now-banned RFS system.

Many race cars have a heave spring to control the car platform in racing, in order to optimise aero yet still allow the car to roll. Rally cars don't, the engineers are allowed four spring (combinations) and two anti-roll bars, and that's it. One way of looking at that is it takes out a lot of work, but compromise must be made at some point and, as Prodrive's technical director David Lapworth points out, "You only need so many variables to achieve the solution we want. But we need one more than we've got!"

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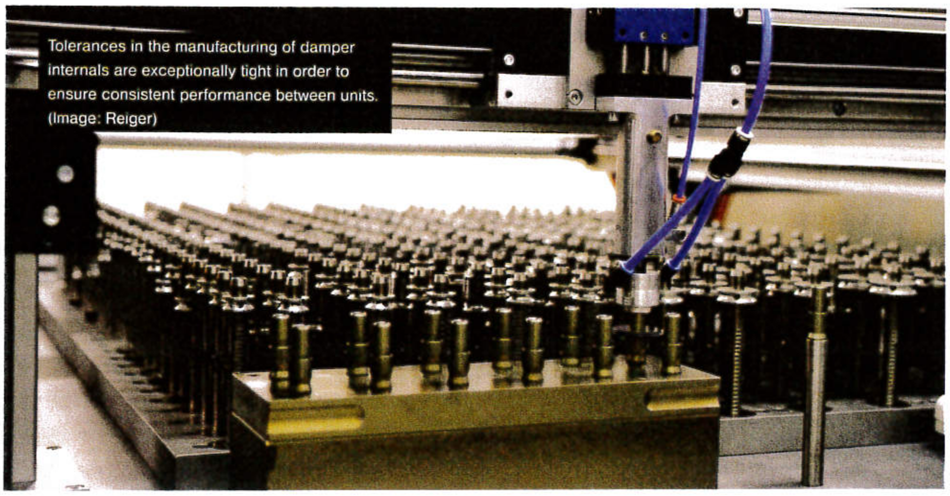

Tolerances in the manufacturing of damper internals are exceptionally tight in order to ensure consistent performance between units. (Image: Reiger)