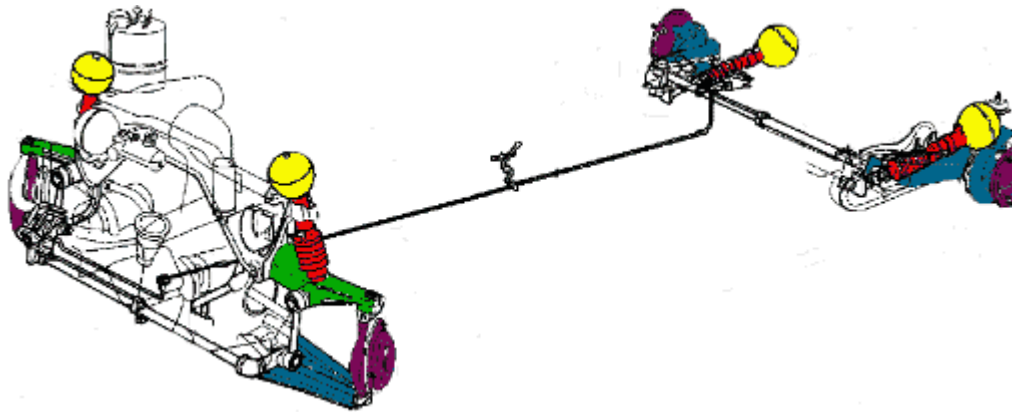


Hydropneumatic Suspension



Since the late forties, Citroën have been running a fundamentally different system to the rest of the auto industry. Its called hydropneumatic suspension, and it is a whole-car solution, which can include the brakes and steering as well as the suspension itself. The core technology of hydropneumatic suspension is as you might guess from the name, hydraulics. Ultra-smooth suspension is provided by the fluid's interaction with a pressurised gas, and in this respect, its very similar to the hydragas system described above. Citroën pioneered the system in the rear suspension of the 15 'Traction Avant' model, and it has been fitted to many of their cars since. Because of the complexity of the system, the rest of this section gets a bit wordy but hopefully not so much that I'll lose you half way through. Because this page is about all types of suspension, for clarity I decided to concentrate on the simplified version of this as installed in the "BX" model. If you're desperate to know every last nut and bolt of hydropneumatics, just do a google search for it.

The system is powered by a large hydraulic pump, typically belt-driven by the engine like an alternator or an air conditioner. The pump provides fluid to an accumulator at pressure, where it is stored ready to be delivered to servo a system. This pump is also used for the power steering and the brakes, and in the DS for the semi-automatic gearbox.

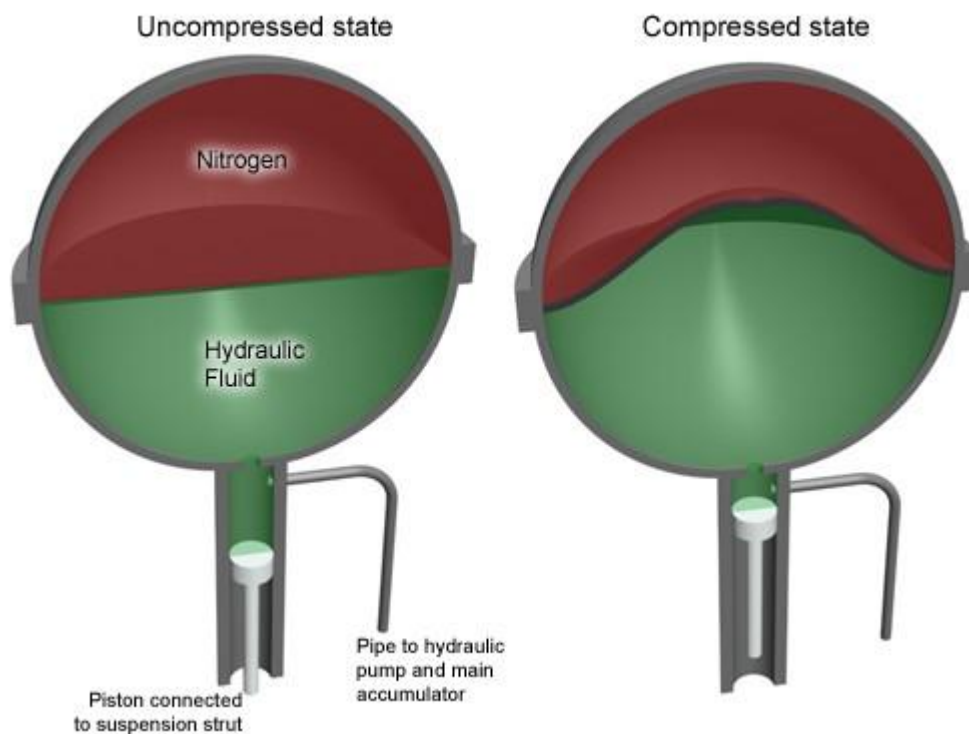
The BX was a major turning point in Citroën's history as it was the first car to be produced under the company's new Peugeot management, following the 1970s take-over. As a direct consequence of the Peugeot influence, the car was somewhat more conventional than its bulkier predecessors like the CX. This Peugeot-enforced "normalisation" of the design makes it fairly easy to examine as an illustration of how hydropneumatic suspension works.

Apart from the pump, the two most obvious components in the system are the spheres on top of each suspension strut, and the struts themselves. The spheres are like the springs in regular suspension, and the struts are the hydraulic components that make the fluid act like a spring.

The spring in this suspension system is provided by a hydraulic component called an accumulator, which is gas (typically nitrogen) under pressure in a bottle contained

within a diaphragm. This is effectively a balloon, which allows pressurised fluid to compress the gas, and then as pressure drops the gas pushes the fluid back to keep the system's pressure up. In the image here, the nitrogen gas is represented in red and the LHM fluid is represented in green. As the pressure in the fluid overcomes the gas pressure, the nitrogen is compressed by the diaphragm being pushed back. Then as the pressure in the fluid reduces, the gas pushes back the diaphragm, which expels the fluid from the sphere, returning gas and fluid to equilibrium. This is the hydropneumatic equivalent to the spring being compressed and then rebounding. We can keep going.

So how can the interaction of compressing gas, hydraulic fluid and a diaphragm form a spring? Simple: The pressure of the gas is the equivalent to the spring weight. The inlet hole at the bottom of the sphere restricts the flow of the fluid and provides an element of damping. By replacing the spheres for ones of different specifications, it's possible to adjust the ride characteristics of these cars.



Before we go any further it is pretty important that you understand where the fluid acting on the diaphragm in the sphere gets its force from, and to do that we are going to have to look at the operation of the other key component in the Citroën system - the strut.

The sphere in these systems is actually mounted at the end of the strut. The strut itself acts like a syringe to inject fluid into the sphere. When the wheel hits a bump it rises, pushes the piston back and this squeezes fluid through the tiny hole in the sphere to let the gas spring absorb the energy of the bump. Then when the car is over the bump, the gas pushes the diaphragm back out, pushing the fluid down to the strut, pushing the wheel down to the ground.

Some interesting possibilities were opened up when Citroën decided to use this system to spring their cars. One or two of the more obvious ones are that since the system is hydraulic, the ride height can easily be altered; Citroën put fancy valves called height correctors in the system. They are designed to correct for long-term/static errors in height. To do this there is a clamp on the middle of each roll bar connected by a linkage to the height corrector. This linkage varies by model - on DS, CX, GS, BX it is a simple torsion bar about 8mm diameter and about 400mm long, on the XM and Xantia it is a coil spring assembly with a double acting override linkage, but the functionality is the same. By measuring the height at the middle of the roll bar, it automatically takes the average of the left and right wheel height on that axle, and therefore cannot detect body roll. This prevents it from spuriously trying to react to body roll, as it can't do anything to counter it anyway - it can only make both sides go up or down together.

Additionally the height correctors have a hydraulic damping chamber in them which restricts and delays their movement - typically it takes a suspension movement of at least 20mm in one direction for at least 5 seconds before the height corrector will respond. Even fully bottoming the suspension still takes at least 5 seconds for a response.

This works as a simple averaging system and prevents the height correctors from responding to bumps or road undulations, (which would be undesirable). The slight exception here is the rear suspension, which is subject to squat due to acceleration because of the front wheel drive. Prolonged heavy acceleration of more than 5 seconds (particularly noticeable on an automatic) will cause a height correction response - an undesirable side effect. (Hydractive 2 models take steps to try and avoid this response by stiffening the suspension during heavy acceleration).

Another noteworthy feature of Citroën system is its ability to "pre-set" a car for bumps in the road, keeping the car on an even keel. This is a result of the cross-piping between left and right struts on the same axle. They are connected permanently via a 3.5mm pipe, (except in Hydractive and Activa systems). The height corrector connects to a T-junction of this cross piping, but when the height corrector is "closed" (which is nearly all the time while driving) it represents a dead end, so only the piping from left to right comes into play. When the wheel on one side hits a bump some oil will flow into the sphere on that side via the damping valve, and some will flow across to the other side and extend the wheel on that side, which gives a slight roll stabilising response. This tends to make the car more steady in the roll axis, and reduces the side-to-side rocking motion on transverse undulations.

A side effect of this cross piping is that it gives the suspension very soft compliance for "warp mode" movements, as the suspension spheres (springing) don't resist slow roll movements like conventional springs do - only the roll bar does. (This improves traction a lot at very slow speeds over very uneven ground) In fact without the roll bars the suspension would be completely unstable on the roll axis - you could sit on the left and it would go right down and the other side would go right up... The downside of the cross connection is the same - the long term roll stiffness is provided only by the roll bar - and there is no damping control of the flow of oil from one side to the other, other than some restriction caused by the small pipe diameter - hence the tendency of older Citroëns to have a lot of very slow body roll. Hydractive 2 overcomes these shortcomings by modifying the side to side connection -

it is increased from 3.5mm to 10mm, but at the mid point there is a unit with an additional sphere, an on/off valve, and two damper valves. In the "soft mode" (selected dynamically by computer) this additional middle sphere is connected in circuit and provides additional springing, via the two damping valves in the unit. The system effectively has two parallel paths for the oil to flow for each bump, with different damping rates. The damper valves in the struts spheres on Hydractive 2 are very stiff, while the ones in the middle unit are softer, giving a net result of 3 stage damping in the soft mode, and 2 stage damping in the hard mode. Any body roll requires oil to either flow into and out of the very stiff damping valves in the strut spheres - where the opening thresholds are above that produced by roll movement - or to flow from side to side - where it must pass through two damping valves in series in the centre unit.

This means roll movements are hydraulically damped in Hydractive systems, unlike Hydropneumatic. This contributes towards the reduced roll on later models like XM and Xantia. Because of the large gauge of pipe there is the potential for greater instantaneous flow when hitting large bumps, so the roll axis stability of the car is actually improved over older models.

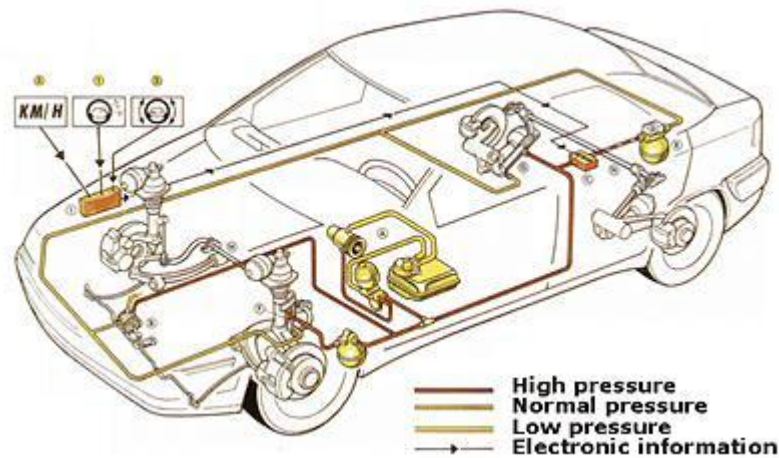
In the "hard mode", again selected dynamically by the computer based on inputs such as steering wheel angle and road speed, the central unit is isolated, completely blocking the cross-flow of oil and isolating the middle sphere, giving stiffer springing, much stiffer damping, and much reduced body roll.

The Activa and Hydractive- 2 refinements / developments were quite effective although only the Xantia has been fitted with it. The main setback was that ride comfort was even worse than a BMW (although cornering speeds were fantastic), which did not go too well with the traditional Citroën clientele. The current adjustable systems (computer controlled) lack this anti roll characteristic, and there are owners who always prefer the "comfort" setting rather than the "sporty" one, because again, that is not what Citroën is about.

A further mechanical advantage of hydraulic suspension is that the car is able to link its braking effort to the weight on the wheels. In the Citroën BX, the rear braking effort comes from the pressure exerted on the LHM fluid by the weight on those struts. This means that as the weight travels forward under braking, there is less pressure on the back suspension. The suspension then exerts less pressure on its fluid, and as weight and grip diminish on the wheels, so does the braking effort, thus the hydropneumatic system prevents rear wheel lock ups.

In addition to these benefits, Citroën pioneered computer controlled suspension in the early nineties by inserting a computer to take readings from the cars' chassis and control systems and let the computer make informed decisions about how to handle the cars suspension. The computer could then effect these decisions by things like servo valves, and offered benefits like soft suspension for cruising, but stiffer, sportier suspension for faster harder driving, allowing the driver to cruise in comfort and still

enjoy a responsive car. It also moves substantially towards eliminating body roll and if used for a sportier driver will save tyre wear as well (they claim).



It's worth noting that when Mercedes launched their latest 600 SLC version with a computer controlled anti roll system, Auto Motor und Sport then proudly claimed that to be the first such anti roll system in world, only having to correct that one issue later by having to mention a French invention.

Hydraulic Suspension

Hydraulic suspension is an innovation making its way into motor sports, no doubt to trickle down to consumer vehicles eventually. It has been designed by a Spanish company called Creuat and pioneered by the *Racing For Holland Dome S101* sports car team. In the image below you can see both the traditional coil over system (the yellow/blue/red units) at the front of the car. This photo was taken before scrutinizing for the 2005 24 Hours of Le Mans race. The team had both systems online and when scrutineering passed the car, the coil over units were removed, to race for the first time completely with hydraulic suspension.

Central to their system is a control unit mounted next to the cockpit. They tell me the system can't be compared to the hydropneumatic suspension Citroën uses because this system doesn't use a pump and has less than a litre of hydraulic fluid in the entire system.

Instead of springs and dampers, this central Hydropneumatic unit takes care of each suspension mode in an independent manner. This allows the car to be tuned to avoid most of the compromises, which arise out of the use of conventional suspension made of springs and dampers.

This system is so new that the best source of information on it is Creuat's own website. You can find it at www.creuat.com and you need to look for the Le Mans Project in their menu on the left side of their page.

Traditional front suspension using coilover units



New hydraulic system. The coilovers have been removed and replaced with solid bars to prevent movement.
The hydraulic units are on the bottom of the pushrods close to the wheel.



Ferrofluid or magneto-rheological fluid dampers - Audi Magnetic Ride.

In 2006, Audi launched the new TT model and one of the innovations that it came with is their magnetic semi-active suspension. It is a totally new form of damping technology developed in conjunction with Delphi (their name for it is [MagneRide](#)). It's designed once again to attempt to resolve the long-standing conflict between cabin comfort and driving dynamics. The Audi system is a continuously adaptive system - i.e. it's a closed feedback loop that can react to changes both in the road surface and the gear-changes (front-to-back weight shift) within milliseconds.

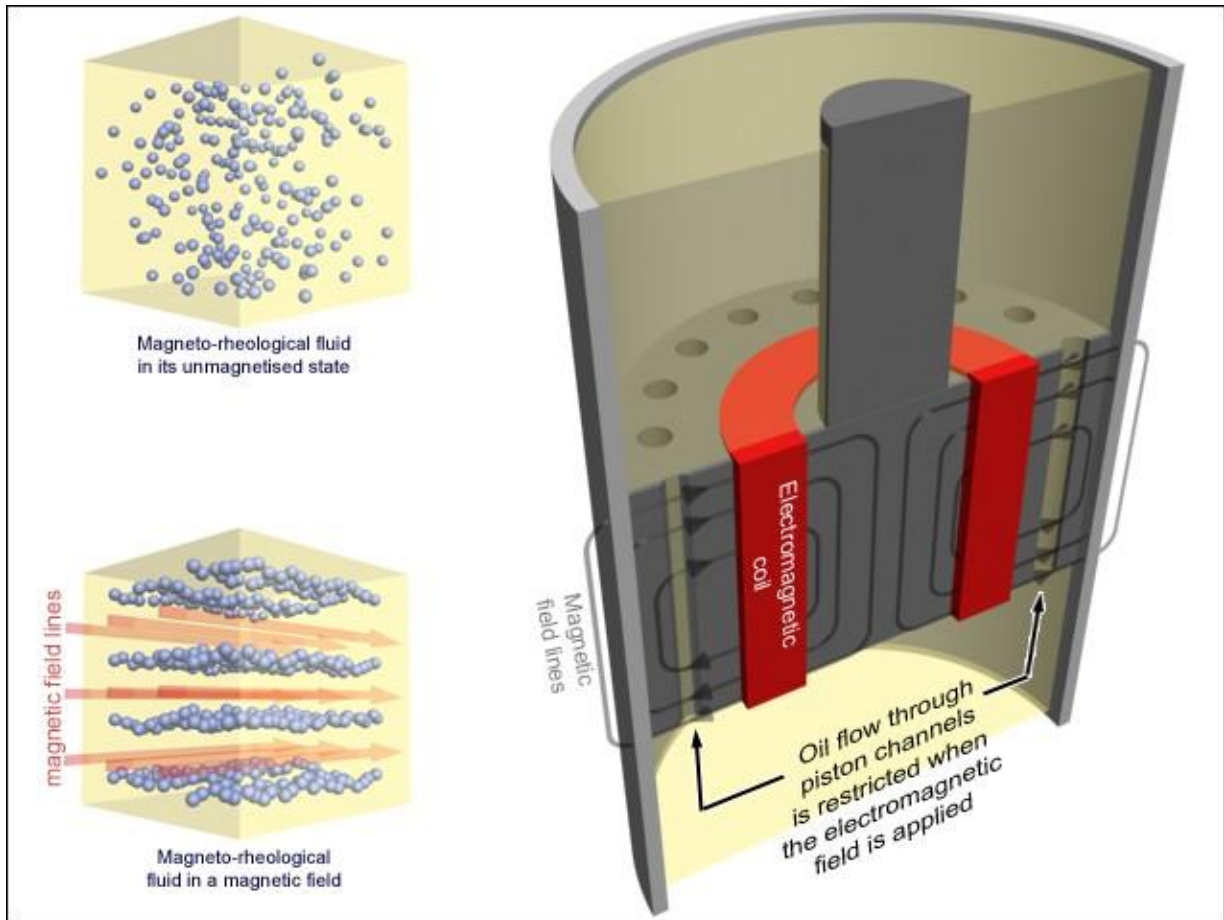


So how does this work? Well, the dampers in the Audi system are not filled with your regular old shock absorber oil. Nope. They're filled with (wait for it) magneto-rheological fluid. This is a synthetic hydrocarbon oil containing sub-miniature magnetic particles. When a voltage is applied to a coil inside the damper piston, it creates a magnetic field (physics 101 - get that old textbook out and check the left- and right-handed electro-magnetic rules that make electric motors work). Inside the magnetic field, all the magnetic particles in the oil change alignment in microseconds to lie predominantly across the damper. Because the damper is trying to squeeze oil up and down through the flow channels, having the particles lined up transverse to this motion makes the oil 'stiffer'. Stiffer oil flows less, which stiffens up the suspension. Neat.

You might have seen a demo of a similar system on TV in 2005 when an artist in New York started making living art using a ferromagnetic liquid (ferro-fluid) and electromagnets. The principle is exactly the same - apply a magnetic field and the fluid lines up along the lines of magnetism. The image on the left shows a ferro-fluid demonstration.

The Audi system has a centralised control unit, which sends signals to the coils on each damper. Hooked up to complex force and acceleration sensing gauges, the control unit constantly analyses what's going on with the car and adjusts the damping settings accordingly. Because there are no moving parts - no valves to open or close - the system reacts within microseconds; far quicker than any other active suspension technology on the market today. And because the amount of voltage applied to the coils can be varied nearly infinitely, the dampers have a similarly near-infinite number of settings. The power usage for each strut is around 5Watts, and the entire thing takes up no more room than a regular coil-over-oil unit. Vorsprung durch Technik indeed.

The diagram below shows the basic principle of magnetised vs. unmagnetised ferrofluid, as well as a cutaway of the piston assembly in a Magneride-type damper. The little blue balls represent the particles of fluid, and yes I know they're huge - that's artistic licence so you can see them.



Linear Electromagnetic Suspension

This is the latest innovation in suspension systems, invented by Bose®. The idea is that instead of springs and shock absorbers on each corner of the car, a single linear electromagnetic motor and power amplifier can be used instead. Inside the linear electromagnetic motor are magnets and coils of wire. When electrical power is applied to the coils, the motor retracts and extends, creating motion between the wheel and car body. It's like the electromagnetic effect used to propel some newer rollercoaster cars on launch, or if you're into videogames and sci-fi, it's like a railgun. One of the big advantages of an electromagnetic approach is speed. The linear electromagnetic motor responds quickly enough to counter the effects of bumps and potholes, thus allowing it to perform the actions previously reserved for shock absorbers.

In its second mode of operation, the system can be used to counter body roll by stiffening the suspension in corners. As well as these functions, it can also be used to raise and lower ride height dynamically. So you could drop the car down low for

motorway cruising, but raise it up for the pothole ridden city streets. It's all very clever.

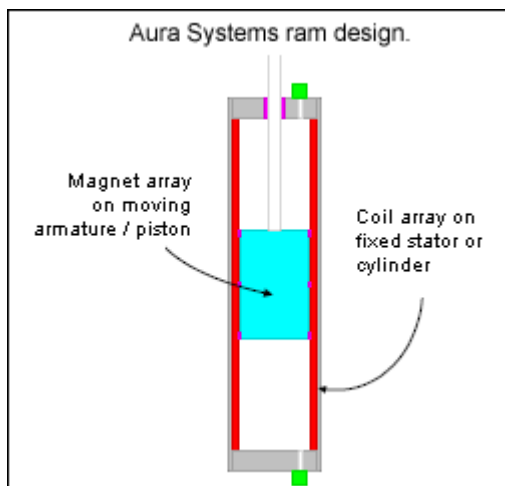


The power amplifier delivers electrical power to the motor in response to signals from the control algorithms. These mathematical algorithms have been developed over 24 years of research. They operate by observing sensor measurements taken from around the car and sending commands to the power amps installed with each linear motor. The goal of the control algorithms is to allow the car to glide smoothly over roads and to eliminate roll and pitch during driving.



The amplifiers themselves are based on switching amplification technologies pioneered by Dr. Bose at MIT in the early 1960s. The really smart thing about the power amps is that they are regenerative. So for example, when the suspension encounters a pothole, power is used to extend the motor and isolate the vehicle's occupants from the disturbance. On the far side of the pothole, the motor operates as a generator and returns power *back* through the amplifier. By doing this, the Bose® system requires less than a third of the power of a typical vehicle's air conditioner system. Clever, eh?

Bose have also managed to package this little wonder of technology into a two-point harness - i.e. it basically needs two bolts to attach it to your vehicle and that's it. It's a pretty compact design, not much bigger than a normal shock absorber.



It's worth noting that a company called Aura Systems devised (or at least tried to market) a similar linear electromagnetic suspension system around 1991. They published an article in the *Automotive Engineering Journal* claiming that electromagnetic actuators could be used for vehicle suspensions and it said that small devices could be designed with a typical thrust capability of about 2500 Newtons and for a reasonable power demand. This happened at the same time that linear electromagnetic rams were being developed for entertainment simulators and full flight simulators to replace hydraulic systems. In fact, it could be argued that the Aura Systems ram was a direct descendant of the rams found on Super-X entertainment simulators.

The units looked very similar to the Bose devices and had the same limitation - they couldn't carry the dead weight of the vehicle. Aura Systems ran into financial troubles in 2000, and filed for Chapter 11 in 2005. The time scales fit quite nicely into the declared Bose time frame (start of development versus going public). Of course they could have been parallel developments, but the bigger question is why was Aura not able to sell their system to an OEM at some time during the previous 15 years? Could it be to do with mechanical limitations - that the sway bars carrying vertical loads are

very good at transmitting road inputs into the vehicle structure even if the bar rate is low? Time will tell if Bose manage to succeed where Aura Systems failed.

Anti-roll Bars & Strut Braces

Strut Braces

If you're serious about your car's handling performance, you will first be looking at lowering the suspension. In most cases, this will be more than adequate. However, if you are a keen driver, you will be able to get far better handling out of your car by fitting a couple of other accessories to it. The first thing you should look at is a strut brace. When you corner, the whole car's chassis is twisting slightly. In the front (and perhaps at the back, but not so often) the suspension pillars will be moving relative to each other because there's no direct physical link between them. They are connected via the car body, which can flex depending on its stiffness. A strut brace bolts across the top of the engine to the tops of the two suspension posts and makes that direct physical contact. The result is that the whole front suspension set up becomes a lot more rigid and there will be virtually no movement relative to each side. In effect, you're adding the fourth side to the open box created by the sub-frame and the two suspension pillars.

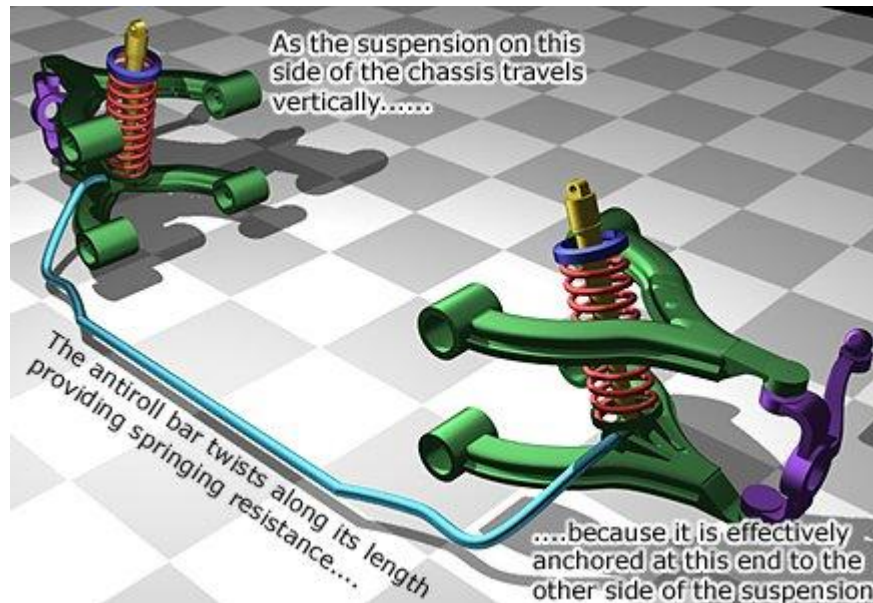


Simple straight brace (highlighted). Complex brace (highlighted).

Anti-roll Bars (Sway Bars/Stabilizers)

No, these aren't the things that are bolted inside the car in case you turn it over - those are rollover cages. Anti-roll bars do precisely what their name implies - they combat the roll of a car on its suspension as it corners. They're also known as sway bars or anti-sway-bars. Almost all cars have them fitted as standard, and if you're a boy-racer, all have scope for improvement. From the factory they are biased towards ride comfort. Stiffer aftermarket items will increase the road holding but you'll get reduced comfort because of it. It's a catch-22 situation. Fiddling with your roll stiffness distribution can make a car uncomfortable to ride in and extremely hard to handle if you get it wrong. The anti-roll bar is usually connected to the front, lower edge of the bottom suspension joint. It passes through two pivot points under the chassis, usually on the sub-frame and is attached to the same point on the opposite suspension set-up. Effectively, it joins the bottom of the suspension parts together. When you head into a corner, the car begins to roll *out* of the corner. For example, if you're cornering to the left, the car body rolls to the right. In doing this, it's compressing the suspension on the right hand side. With a good anti-roll bar, as the lower part of the suspension moves upward relative to the car chassis, it transfers some of that movement to the

same component on the other side. In effect, it tries to lift the left suspension component by the same amount. Because this isn't physically possible, the left suspension effectively becomes a fixed point and the anti-roll bar twists along its length because the other end is effectively anchored in place. It's this twisting that provides the resistance to the suspension movement.



If you're loaded, you can buy cars with active anti-roll technology now. These sense the roll of the car into a corner and deflate the relevant suspension leg accordingly by pumping fluid in and out of the shock absorber. It's a high-tech, super expensive version of the good old mechanical anti-roll bar. You can buy anti-roll bars as an aftermarket add-on. They're relatively easy to fit because most cars have anti-roll bars already. Take the old one off and fit the new one. In the case of rear suspension, the fittings will probably already be there even if the anti-roll bar isn't.



Typical anti-roll bar (sway-bar) kits include the up-rated bar, a set of new mounting clamps with polyurethane bushes, rose joints for the ends, which connect, to the suspension components, and all the bolts etc that will be needed.

Suspension bushes



These are the rubber grommets, which separate most of the parts of your suspension from each other. They're used at the link of an A-Arm with the sub-frame. They're used on anti-roll bar links and mountings. They're used all over the place, and from the factory, I can almost guarantee they're made of rubber. Rubber doesn't last. It perishes in the cold and splits in the heat. Perished, split rubber was what brought the Challenger space shuttle down. This is one of those little parts, which hardly anyone pays any attention to, but it's vitally important for your car's handling, as well as your own safety, that these little things are in good condition. My advice? Replace them with polyurethane or polygraphite bushes - they are hardwearing and last a heck of a lot longer. And, if you're into presenting your car at shows, they look better than the naff little black rubber jobs. Like all suspension-related items though, bushes are a trade-off between performance and comfort. The harder the bush compounds, the less comfort in the cabin.

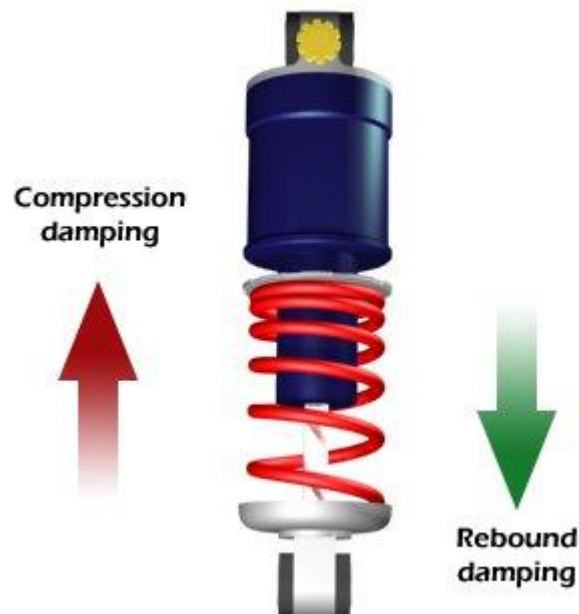
The Ins and Outs of complex suspension units.

Generally speaking, this section will be more relevant to you if you ride a motorbike, but you can get high-end spring / shock combos for cars that have all these features on them.

Compression damping.

This is the damping that a shock absorber provides as it's being compressed, i.e. as you hit a bump in the road. It's the resistance of the unit to alter from its steady state to its compressed state. Imagine you're riding along and you hit a bump. If there is too little compression damping, the wheel will not meet enough resistance as the suspension compresses. Not enough energy is dissipated by the time you reach the crest of the bump and because the wheel and other un-sprung components have their own mass, the wheel will continue to move upwards. This un-weights or unloads the tyre and in extreme cases, it can lose contact with the road. Either way, you briefly lose traction and control.

The opposite is true if compression damping is too heavy. As the wheel encounters the bump in the road, the resistance to moving is high and so at the crest of the bump, the remaining energy from the upward motion through the shock absorber is transferred into the frame of the bike or the chassis of the car, lifting it up.



Rebound damping.

This is the damping that a shock absorber provides as it returns from its compressed state to its steady state, i.e. after you've crested the bump in the road. Too light, and the feeling of control in your vehicle is minimised because the wheel will move very quickly. The feeling is the soft, plush ride you find in a lot of American cars. Or 'mushy' as we like to call it. Too heavy, and the shock absorber can't return quickly enough. As the contour of the road drops away after the bump, the wheel has a hard time "catching up". This can result in reduced traction, and a downward shift in the height of the vehicle. If that happens, you can overload the tyre when the weight of the vehicle bottoms-out the suspension.

Damping controllers.

High-end kit has controls on the shock absorber for both compression and rebound damping. Typically the rebound damping will be a screwdriver slot at the top of the shock absorber, and compression damping will be a knob either on the side or on the remote reservoir. Ultra-high-end kit has separate controls for high- and low-speed damping. ie. you can make the shock absorber behave differently over small bumps (low speed compression and rebound) than it does over large bumps (high speed compression and rebound).

Spring preload.

Some motorbike suspension units, as well as some found on cars, give you the ability to alter the spring preload or pre-tension. This means that you're artificially compressing the spring, a little, which will alter the vehicle's static sag - the amount of suspension travel the vehicle consumes all by itself. For example, if you ride a motorbike on your own, the preload might work on the factory set-up. But if you put a passenger on the back, the tendency is for the bike to sag because there's now more sprung weight. Increasing the preload on the spring plate will help compensate for this.

Sprung vs. un-sprung weight.

Simply put, sprung weight is everything from the springs up, and un-sprung weight is everything from the springs down. Wheels, shock absorbers, springs, knuckle joints and tyres contribute to the un-sprung weight. The car, engine, fluids, you, your passenger, the kids, the bags of candy and the portable PlayStation all contribute to the sprung weight. Reducing un-sprung weight is the key to increasing performance of the car. If you can make the wheels, tyres and swing-arms lighter, then the suspension will spend more time compensating for bumps in the road, and less time compensating for the mass of the wheels etc.

The greater the un-sprung weight, the greater the inertia of the suspension, which will be unable to respond as quickly to rapid changes in the road surface. As an added benefit, putting lighter wheels on the car can increase your engine's apparent power. Why? Well the engine has to turn the gearbox and drive shafts, and at the end of that, the wheels and tyres. Heavier wheels and tyres require more torque to get turning, which saps engine power. Lighter wheels and tyres allow more of the engine's torque to go into getting you going than spinning the wheels. That's why sports cars have carbon fibre drive shafts and ultra light alloy wheels.

Electronic damping force controllers.



In 2005 the aftermarket saw the first appearance of an EDFC - electronic damping force controller.

The premise is really simple. Four servo motors (the four smaller boxes in the picture here), one for each strut, each one designed to replace the manual screw adjuster. A control unit mounts inside the car and allows you to change the damping force of the shocks front and rear without leaving the drivers seat. The way it works is dead simple. When you first install the system and power it up, all the servos spin clockwise for a few seconds. This ensures the adjusters are screwed all the way in on all four struts. From that point, you can dial in any number from 0 to 20 on the control unit. When you do, the servo motors spin a certain amount - the same as you getting out of the car and spinning the adjuster with your finely calibrated fingers. The units

currently have three memory settings so you can store motorway, city and track-day settings (for example), and recall them at the push of a button.

Installing the current-generation EDFCs is pretty simple - about the most difficult thing you'll face is running the wires from each servo back to the control unit inside the car.

Torsion bars

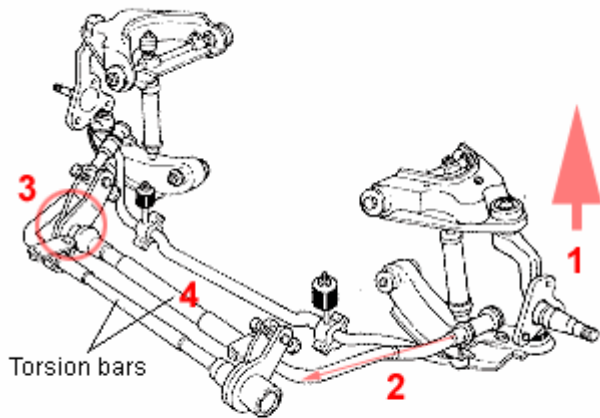


Torsion bars deserve their own section because they are a type of spring, which can be used in place of coil- or leaf springs. It's one of the topics I get the most e-mail on, so instead of continually sending the same answer, I thought I'd cover it on this page.

A torsion bar is a solid bar of steel, which is connected to the car chassis at one end, and free to move at the other end. They are almost always mounted across the car, one for each side of the suspension. The springing motion is provided by the metal bar's resistance to twisting. To over-simplify, stick your arm out straight and get someone to twist your wrist. Presuming that your mate doesn't snap your wrist, at a certain point, resistance in your arm (and pain) will cause you to twist your wrist back the other way. That is the principle of a torsion bar.

Torsion bars typically have splines on one end so that they can be removed, twisted round one spline and re-inserted. This can be used to raise or lower a car, or to compensate for the natural 'sag' of a suspension system over time.

Transverse torsion arms mounted across the chassis



- [1] Suspension compresses
- [2] Control arm twists the torsion bar
- [3] Torsion bar is anchored at one end
- [4] Torsion bar resists twisting and provides spring

A longitudinal torsion bar mounted along the chassis

