



Automotive Suspension Technologies

Jefferey Cornell

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Chapter 1

Suspension (Vehicle)



The front suspension components of a Ford Model T.



The rear suspension on a truck: a leaf spring.



Part of car front suspension and steering mechanism: tie rod, steering arm, king pin axis (using ball joints).

Suspension is the term given to the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. Suspension systems serve a dual purpose — contributing to the car's roadholding/handling and braking for good active safety and driving pleasure, and keeping vehicle occupants comfortable and reasonably well isolated from road noise, bumps, and vibrations, etc. These goals are generally at odds, so the tuning of suspensions involves finding the right compromise. It is important for the suspension to keep the road wheel in contact with the road surface as much as possible, because all the forces acting on the vehicle do so through the contact patches of the tires. The suspension also protects the vehicle itself and any cargo or luggage from damage and wear. The design of front and rear suspension of a car may be different.

History

Leaf springs have been around since the early Egyptians.

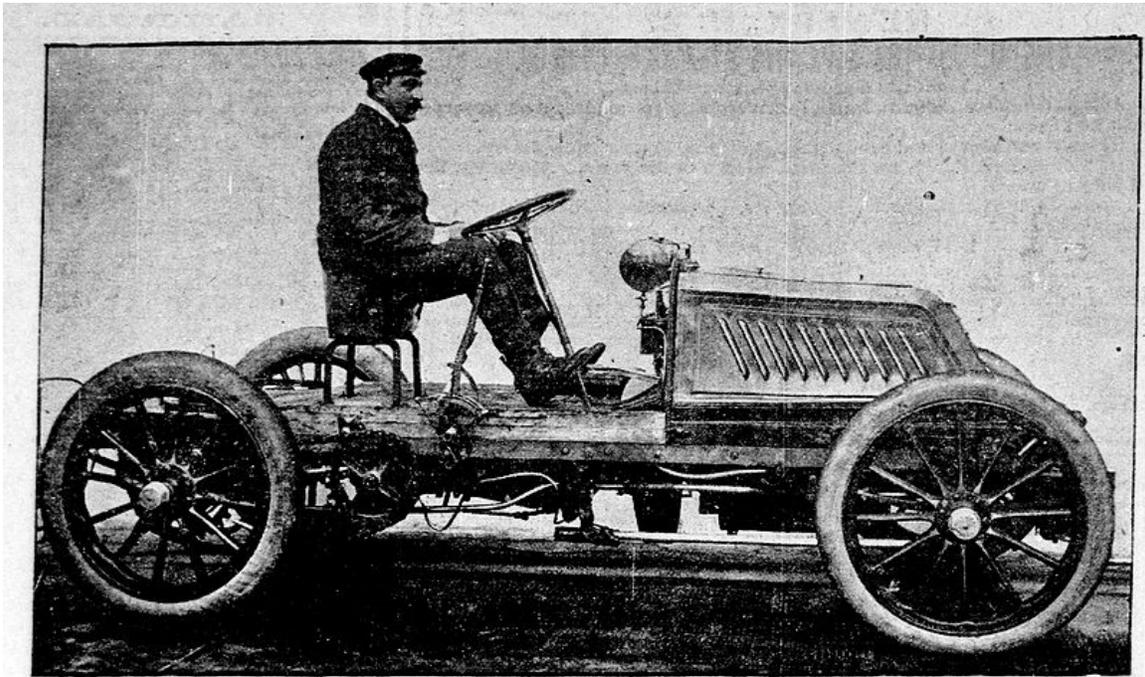
Ancient military engineers used leaf springs in the form of bows to power their siege engines, with little success at first. The use of leaf springs in catapults was later refined and made to work years later. Springs were not only made of metal, a sturdy tree branch could be used as a spring, such as with a bow.

Horse drawn vehicles

By the early 19th century, most British horse carriages were equipped with springs; wooden springs in the case of light one-horse vehicles to avoid taxation, and steel springs in larger vehicles. These were made of low-carbon steel and usually took the form of multiple layer leaf springs.

The British steel springs were not well suited for use on America's rough roads of the time, and could even cause coaches to collapse if cornered too fast. In the 1820s, the Abbot Downing Company of Concord, New Hampshire developed a system whereby the bodies of stagecoaches were supported on leather straps called "thoroughbraces", which gave a swinging motion instead of the jolting up and down of a spring suspension (the stagecoach itself was sometimes called a "thoroughbrace").

Automobiles



FOURNIER ON THE "MORS" MACHINE WITH WHICH HE WON THE PARIS-BORDEAUX AND PARIS-BERLIN RACES AND BEAT THE VANDERBILT RECORD FOR ONE KILOMETRE.

Henri Fournier on his uniquely dampened and racewinning 'Mors Machine', photo taken 1902

Automobiles were initially developed as self-propelled versions of horse drawn vehicles. However, horse drawn vehicles had been designed for relatively slow speeds and their suspension was not well suited to the higher speeds permitted by the internal combustion engine.

In 1901 Mors of Germany first fitted an automobile with shock absorbers. With the advantage of having a dampened suspension system in his 'Mors Machine', Henri Fournier was able to win the prestigegous Paris — Berlin race on June 20, 1901. Fourniers superior time was 11 hrs 46 min 10 sec, while the best competitor was Léonce Girardot in a Panhard at the time 12 hrs 15 min 40 sec.

In 1920, Leyland used torsion bars in a suspension system. In 1922, independent front suspension was pioneered on the Lancia Lambda and became more common in mass market cars from 1932.

Important properties



Citroën BX Hydropneumatic suspension - maximum to minimum demonstration

Spring rate

The spring rate (or suspension rate) is a component in setting the vehicle's ride height or its location in the suspension stroke. Vehicles which carry heavy loads will often have

heavier springs to compensate for the additional weight that would otherwise collapse a vehicle to the bottom of its travel (stroke). Heavier springs are also used in performance applications where the loading conditions experienced are more extreme.

Springs that are too hard or too soft cause the suspension to become ineffective because they fail to properly isolate the vehicle from the road. Vehicles that commonly experience suspension loads heavier than normal have heavy or hard springs with a spring rate close to the upper limit for that vehicle's weight. This allows the vehicle to perform properly under a heavy load when control is limited by the inertia of the load. Riding in an empty truck used for carrying loads can be uncomfortable for passengers because of its high spring rate relative to the weight of the vehicle. A race car would also be described as having heavy springs and would also be uncomfortably bumpy. However, even though we say they both have heavy springs, the actual spring rates for a 2,000 lb (910 kg) race car and a 10,000 lb (4,500 kg) truck are very different. A luxury car, taxi, or passenger bus would be described as having soft springs. Vehicles with worn out or damaged springs ride lower to the ground which reduces the overall amount of compression available to the suspension and increases the amount of body lean. Performance vehicles can sometimes have spring rate requirements other than vehicle weight and load.

Mathematics of the spring rate

Spring rate is a ratio used to measure how resistant a spring is to being compressed or expanded during the spring's deflection. The magnitude of the spring force increases as deflection increases according to Hooke's Law. Briefly, this can be stated as

$$F = -kx$$

where

F is the force the spring exerts

k is the spring rate of the spring.

x is the displacement from equilibrium length i.e. the length at which the spring is neither compressed or stretched.

Spring rate is confined to a narrow interval by the weight of the vehicle, load the vehicle will carry, and to a lesser extent by suspension geometry and performance desires.

Spring rates typically have units of N/mm (or lbf/in). An example of a linear spring rate is 500 lbf/in. For every inch the spring is compressed, it exerts 500 lbf. A non-linear spring rate is one for which the relation between the spring's compression and the force exerted cannot be fitted adequately to a linear model. For example, the first inch exerts 500 lbf force, the second inch exerts an additional 550 lbf (for a total of 1050 lbf), the third inch exerts another 600 lbf (for a total of 1650 lbf). In contrast a 500 lbf/in linear spring compressed to 3 inches will only exert 1500 lbf.

The spring rate of a coil spring may be calculated by a simple algebraic equation or it may be measured in a spring testing machine. The spring constant k can be calculated as follows:

$$k = \frac{d^4 G}{8ND^3}$$

where d is the wire diameter, G is the spring's shear modulus (e.g., about 12,000,000 lbf/in² or 80 GPa for steel), and N is the number of wraps and D is the diameter of the coil.

Wheel rate

Wheel rate is the effective spring rate when measured at the wheel. This is as opposed to simply measuring the spring rate alone.

Wheel rate is usually equal to or considerably less than the spring rate. Commonly, springs are mounted on control arms, swing arms or some other pivoting suspension member. Consider the example above where the spring rate was calculated to be 500 lbs/inch, if you were to move the wheel 1 in (2.5 cm) (without moving the car), the spring more than likely compresses a smaller amount. Lets assume the spring moved 0.75 in (19 mm), the lever arm ratio would be 0.75:1. The wheel rate is calculated by taking the square of the ratio (0.5625) times the spring rate. Squaring the ratio is because the ratio has two effects on the wheel rate. The ratio applies to both the force and distance traveled.

Wheel rate on independent suspension is fairly straight-forward. However, special consideration must be taken with some non-independent suspension designs. Take the case of the straight axle. When viewed from the front or rear, the wheel rate can be measured by the means above. Yet because the wheels are not independent, when viewed from the side under acceleration or braking the pivot point is at infinity (because both wheels have moved) and the spring is directly inline with the wheel contact patch. The result is often that the effective wheel rate under cornering is different from what it is under acceleration and braking. This variation in wheel rate may be minimized by locating the spring as close to the wheel as possible.

Roll couple percentage

Roll couple percentage is the effective wheel rate, in roll, of each axle of the vehicle as a ratio of the vehicle's total roll rate. Roll couple percentage is critical in accurately balancing the handling of a vehicle. It is commonly adjusted through the use of anti-roll bars, but can also be changed through the use of different springs.

A vehicle with a roll couple percentage of 70% will transfer 70% of its sprung weight at the front of the vehicle during cornering. This is also commonly known as "Total Lateral Load Transfer Distribution" or "TLLTD".

Weight transfer

Weight transfer during cornering, acceleration or braking is usually calculated per individual wheel and compared with the static weights for the same wheels.

The total amount of weight transfer is only affected by four factors: the distance between wheel centers (wheelbase in the case of braking, or track width in the case of cornering) the height of the center of gravity, the mass of the vehicle, and the amount of acceleration experienced.

The speed at which weight transfer occurs as well as through which components it transfers is complex and is determined by many factors including but not limited to roll center height, spring and damper rates, anti-roll bar stiffness and the kinematic design of the suspension links.

Unsprung weight transfer

Unsprung weight transfer is calculated based on the weight of the vehicle's components that are not supported by the springs. This includes tires, wheels, brakes, spindles, half the control arm's weight and other components. These components are then (for calculation purposes) assumed to be connected to a vehicle with zero sprung weight. They are then put through the same dynamic loads. The weight transfer for cornering in the front would be equal to the total unsprung front weight times the G-Force times the front unsprung center of gravity height divided by the front track width. The same is true for the rear.

Sprung weight transfer

Sprung weight transfer is the weight transferred by only the weight of the vehicle resting on the springs, not the total vehicle weight. Calculating this requires knowing the vehicle's sprung weight (total weight less the unsprung weight), the front and rear roll center heights and the sprung center of gravity height (used to calculate the roll moment arm length). Calculating the front and rear sprung weight transfer will also require knowing the roll couple percentage.

The roll axis is the line through the front and rear roll centers that the vehicle rolls around during cornering. The distance from this axis to the sprung center of gravity height is the roll moment arm length. The total sprung weight transfer is equal to the G-force times the sprung weight times the roll moment arm length divided by the effective track width. The front sprung weight transfer is calculated by multiplying the roll couple percentage times the total sprung weight transfer. The rear is the total minus the front transfer.

Jacking forces

Jacking forces are the sum of the vertical force components experienced by the suspension links. The resultant force acts to lift the sprung mass if the roll center is above

ground, or compress it if underground. Generally, the higher the roll center, the more jacking force is experienced.

Travel

Travel is the measure of distance from the bottom of the suspension stroke (such as when the vehicle is on a jack and the wheel hangs freely) to the top of the suspension stroke (such as when the vehicle's wheel can no longer travel in an upward direction toward the vehicle). Bottoming or lifting a wheel can cause serious control problems or directly cause damage. "Bottoming" can be caused by the suspension, tires, fenders, etc. running out of space to move or the body or other components of the car hitting the road. The control problems caused by lifting a wheel are less severe if the wheel lifts when the spring reaches its unloaded shape than they are if travel is limited by contact of suspension members. Many off-road vehicles, such as desert racers, use straps called "limiting straps" to limit the suspensions downward travel to a point within safe limits for the linkages and shock absorbers. This is necessary, since these trucks are intended to travel over very rough terrain at high speeds, and even become airborne at times. Without something to limit the travel, the suspension bushings would take all the force when the suspension reaches "full droop", and it can even cause the coil springs to come out of their "buckets" if they are held in by compression forces only. A limiting strap is a simple strap, often nylon of a predetermined length, that stops the downward movement at a preset point before the theoretical maximum travel is reached. The opposite of this is the "bump-stop", which protects the suspension and vehicle (as well as the occupants) from violent "bottoming" of the suspension, caused when an obstruction (or hard landing) causes the suspension to run out of upward travel without fully absorbing the energy of the stroke. Without bump-stops, a vehicle that "bottoms out" will experience a very hard shock when the suspension contacts the bottom of the frame or body, which is transferred to the occupants and every connector and weld on the vehicle. Factory vehicles often come with plain rubber "nubs" to absorb the worst of the forces, and insulate the shock. A desert race vehicle, which must routinely absorb far higher impact forces, may be provided with pneumatic or hydro-pneumatic bump-stops. These are essentially miniature shock absorbers (dampeners) that are fixed to the vehicle in a location such that the suspension will contact the end of the piston when it nears the upward travel limit. These absorb the impact far more effectively than a solid rubber bump-stop will, essential because a rubber bump-stop is considered a "last-ditch" emergency insulator for the occasional accidental bottoming of the suspension; it is entirely insufficient to absorb repeated and heavy bottomings such as a high-speed off road vehicle encounters.

Damping

Damping is the control of motion or oscillation, as seen with the use of hydraulic gates and valves in a vehicles shock absorber. This may also vary, intentionally or unintentionally. Like spring rate, the optimal damping for comfort may be less than for control.

Damping controls the travel speed and resistance of the vehicle's suspension. An undamped car will oscillate up and down. With proper damping levels, the car will settle back to a normal state in a minimal amount of time. Most damping in modern vehicles can be controlled by increasing or decreasing the resistance to fluid flow in the shock absorber.

Camber control

Camber changes due to wheel travel, body roll and suspension system deflection or compliance. In general, a tire wears and brakes best at -1 to -2° of camber from vertical. Depending on the tire and the road surface, it may hold the road best at a slightly different angle. Small changes in camber, front and rear, can be used to tune handling. Some race cars are tuned with $-2\sim-7^\circ$ camber depending on the type of handling desired and the tire construction. Oftentimes, too much camber will result in the decrease of braking performance due to a reduced contact patch size through excessive camber variation in the suspension geometry. The amount of camber change in bump is determined by the instantaneous front view swing arm (FVSA) length of the suspension geometry, or in other words, the tendency of the tire to camber inward when compressed in bump.

Roll center height

This is important to body roll and to front to rear roll stiffness distribution. However, the roll stiffness distribution in most cars is set more by the antiroll bars than the RCH. The height of the roll center is related to the amount of jacking forces experienced.

Instant center

Due to the fact that the wheel and tire's motion is constrained by the suspension links on the vehicle, the motion of the wheel package in the front view will scribe an imaginary arc in space with an "instantaneous center" of rotation at any given point along its path. The instant center for any wheel package can be found by following imaginary lines drawn through the suspension links to their intersection point.

A component of the tire's force vector points from the contact patch of the tire through instant center. The larger this component is, the less suspension motion will occur. Theoretically, if the resultant of the vertical load on the tire and the lateral force generated by it points directly into the instant center, the suspension links will not move. In this case, all weight transfer at that end of the vehicle will be geometric in nature. This is key information used in finding the force-based roll center as well.

In this respect the instant centers are more important to the handling of the vehicle than the kinematic roll center alone, in that the ratio of geometric to elastic weight transfer is determined by the forces at the tires and their directions in relation to the position of their respective instant centers.

No-dive and No-squat

Anti-dive and anti-squat are percentages and refer to the front diving under braking and the rear squatting under acceleration. They can be thought of as the counterparts for braking and acceleration as jacking forces are to cornering. The main reason for the difference is due to the different design goals between front and rear suspension, whereas suspension is usually symmetrical between the left and right of the vehicle.

The method of determining the anti-dive or anti-squat depends on whether the suspension linkages react to the torque of braking and accelerating. For example, with inboard brakes and half-shaft driven rear wheels, the suspension linkages do not, but with outboard brakes and a swing-axle driveline, they do.

To determine the percentage of front suspension braking anti-dive for outboard brakes, it is first necessary to determine the tangent of the angle between a line drawn, in side view, through the front tire patch and the front suspension instant center, and the horizontal. In addition, the percentage of braking effort at the front wheels must be known. Then, multiply the tangent by the front wheel braking effort percentage and divide by the ratio of the center of gravity height to the wheelbase. A value of 50% would mean that half of the weight transfer to the front wheels, during braking, is being transmitted through the front suspension linkage and half is being transmitted through the front suspension springs.

For inboard brakes, the same procedure is followed but using the wheel center instead of contact patch center.

Forward acceleration anti-squat is calculated in a similar manner and with the same relationship between percentage and weight transfer. Anti-squat values of 100% and more are commonly used in dragracing, but values of 50% or less are more common in cars which have to undergo severe braking. Higher values of anti-squat commonly cause wheel hop during braking. It is important to note that, while the value of 100%...in either case...means that all of the weight transfer is being carried through the suspension linkage, this does not mean that the suspension is incapable of carrying additional loads (aerodynamic, cornering, etc.) during an episode of braking or forward acceleration. In other words, no "binding" of the suspension is to be implied.

Flexibility and vibration modes of the suspension elements

In modern cars, the flexibility is mainly in the rubber bushings. For high-stress suspensions, such as off-road vehicles, polyurethane bushings are available, which offer far more longevity under greater stresses.

Isolation from high frequency shock

For most purposes, the weight of the suspension components is unimportant, but at high frequencies, caused by road surface roughness, the parts isolated by rubber bushings act

as a multistage filter to suppress noise and vibration better than can be done with only the tires and springs. (The springs work mainly in the vertical direction.)

Contribution to unsprung weight and total weight

These are usually small, except that the suspension is related to whether the brakes and differential(s) are sprung.

Space occupied

Designs differ as to how much space they take up and where it is located. It is generally accepted that MacPherson struts are the most compact arrangement for front-engined vehicles, where space between the wheels is required to place the engine.

Force distribution

The suspension attachment must match the frame design in geometry, strength and rigidity.

Air resistance (drag)

Certain modern vehicles have height adjustable suspension in order to improve aerodynamics and fuel efficiency. And modern formula cars, that have exposed wheels and suspension, typically use streamlined tubing rather than simple round tubing for their suspension arms to reduce drag. Also typical is the use of rocker arm, push rod, or pull rod type suspensions, that among other things, places the spring/damper unit inboard and out of the air stream to further reduce air resistance.

Cost

Production methods improve, but cost is always a factor. The continued use of the solid rear axle, with unsprung differential, especially on heavy vehicles, seems to be the most obvious example.

Springs and dampers

Most conventional suspensions use passive springs to absorb impacts and dampers (or shock absorbers) to control spring motions.

Some notable exceptions are the hydropneumatic systems, which can be treated as an integrated unit of gas spring and damping components, used by the French manufacturer Citroën and the hydrolastic, hydragas and rubber cone systems used by the British Motor Corporation, most notably on the Mini. A number of different types of each have been used:

Passive suspensions

Traditional springs and dampers are referred to as passive suspensions — most vehicles are suspended in this manner.

Springs



Pneumatic spring on a semitrailer

- Leaf spring – AKA Hotchkiss, Cart, or semi-elliptical spring
- Torsion beam suspension
- Coil spring
- Rubber bushing
- Air spring

Dampers or shock absorbers

The shock absorbers damp out the (otherwise resonant) motions of a vehicle up and down on its springs. They also must damp out much of the wheel bounce when the unsprung weight of a wheel, hub, axle and sometimes brakes and differential bounces up and down on the springiness of a tire. The regular bumps found on dirt roads (nicknamed "corduroy", but properly corrugations or washboarding) are caused by this wheel bounce.

Semi-active and active suspensions

If the suspension is externally controlled then it is a semi-active or active suspension — the suspension is reacting to what are in effect "brain" signals. As electronics have become more sophisticated, the opportunities in this area have expanded.

For example, a hydropneumatic Citroën will "know" how far off the ground the car is supposed to be and constantly reset to achieve that level, regardless of load. It will *not* instantly compensate for body roll due to cornering however. Citroën's system adds about 1% to the cost of the car versus passive steel springs.

Semi-active suspensions include devices such as air springs and switchable shock absorbers, various self-levelling solutions, as well as systems like Hydropneumatic, Hydrolastic, and Hydragas suspensions. Mitsubishi developed the world's first production semi-active electronically controlled suspension system in passenger cars; the system was first incorporated in the 1987 Galant model. Delphi currently sells shock absorbers filled with a magneto-rheological fluid, whose viscosity can be changed electromagnetically, thereby giving variable control without switching valves, which is faster and thus more effective.

Fully active suspension systems use electronic monitoring of vehicle conditions, coupled with the means to impact vehicle suspension and behavior in real time to directly control the motion of the car. Lotus Cars developed several prototypes, from 1982 onwards, and introduced them to F1, where they have been fairly effective, but have now been banned. Nissan introduced a low bandwidth active suspension in circa 1990 as an option that added an extra 20% to the price of luxury models. Citroën has also developed several active suspension models. A recently publicised fully active system from Bose Corporation uses linear electric motors, i.e. solenoids, in place of hydraulic or pneumatic actuators that have generally been used up until recently. The most advanced suspension system is Active Body Control, introduced in 1999 on the top-of-the-line Mercedes-Benz CL-Class.

Several electromagnetic suspensions have also been developed for vehicles. Examples include the electromagnetic suspension of Bose, and the electromagnetic suspension developed by prof. Laurentiu Encica. In addition, the new Michelin wheel with embedded suspension working on a electromotor is also similar.

With the help of control system, various semi-active/active suspensions realize an improved design compromise among different vibrations modes of the vehicle, namely bounce, roll, pitch and warp modes. However, the applications of these advanced suspensions are constrained by the cost, packaging, weight, reliability, and/or the other challenges.

Interconnected suspensions

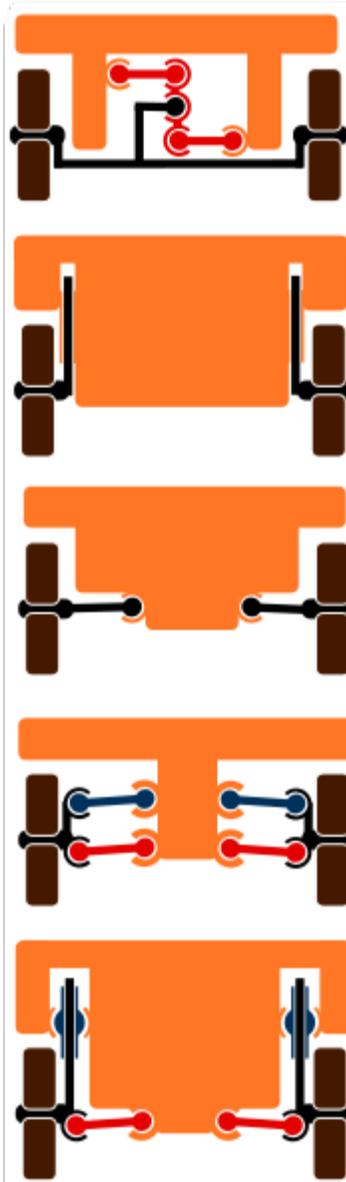
Interconnected suspension, unlike semi-active/active suspensions, could easily decouple different vehicle vibration modes in a passive manner. The interconnections can be realized by various means, such as mechanical, hydraulic and pneumatic. Anti-roll bars are one of the typical examples of mechanical interconnections, while it has been stated that fluidic interconnections offer greater potential and flexibility in improving both the stiffness and damping properties.

Considering the considerable commercial potentials of hydro-pneumatic technology (Corolla, 1996), interconnected hydropneumatic suspensions have also been explored in some recent studies, and their potential benefits in enhancing vehicle ride and handling have been demonstrated. The control system can also be used for further improving performance of interconnected suspensions. Apart from academic research, an Australian company, Kinetic, is having some success (WRC: 3 Championships, Dakar Rally: 2 Championships, Lexus GX470 2004 4x4 of the year with KDSS, 2005 PACE award) with various passive or semi-active systems, which generally decouple at least two vehicle modes (roll, warp (articulation), pitch and/or heave (bounce)) to simultaneously control each mode's stiffness and damping, by using interconnected shock absorbers, and other methods. In 1999, Kinetic was bought out by Tenneco.

Historically, the first mass production car with front to rear mechanical interconnected suspension was the 1948 Citroën 2CV. The suspension of the 2CV was extremely soft — it had low roll stiffness, but its pitch stiffness was increased by using an interconnected suspension. The leading arm / trailing arm swinging arm, fore-aft linked suspension system together with inboard front brakes had a much smaller unsprung weight than existing coil spring or leaf designs. The interconnection transmitted some of the force deflecting a front wheel up over a bump, to push the rear wheel down on the same side. When the rear wheel met that bump a moment later, it did the same in reverse, keeping the car level front to rear. The 2CV had a design brief to be able to be driven at speed over a ploughed field. It originally featured friction dampers and tuned mass dampers. Later models had tuned mass dampers at the front with telescopic dampers / shock absorbers front and rear.

Some of the last post-war Packard models also featured interconnected suspension. The original Mini and some more recent British Leyland models also featured interlinking, when fitted with Moulton's Hydrolastic or Hydragas suspensions.

Suspension Geometry



Common types seen from behind. From top to bottom: live axle with Watt bar, suspension like on a bike fork, swing axle, double wishbone, MacPherson. Some types are missing because trailing arm links are not presentable in this view and some types use elements which flex to some movements and are stiff to others and flexible elements are omitted for clarity.

Suspension systems can be broadly classified into two subgroups — dependent and independent. These terms refer to the ability of opposite wheels to move independently of each other.

A dependent suspension normally has a beam (a simple 'cart' axle) or (driven) live axle that holds wheels parallel to each other and perpendicular to the axle. When the camber

of one wheel changes, the camber of the opposite wheel changes in the same way (by convention on one side this is a positive change in camber and on the other side this a negative change). De Dion suspensions are also in this category as they rigidly connect the wheels together.

An *independent suspension* allows wheels to rise and fall on their own without affecting the opposite wheel. Suspensions with other devices, such as sway bars that link the wheels in some way are still classed as independent.

A third type is a *semi-dependent* suspension. In this case, the motion of one wheel does affect the position of the other but they are not rigidly attached to each other. A twist-beam rear suspension is such a system.

Dependent suspensions

Dependent systems may be differentiated by the system of linkages used to locate them, both longitudinally and transversely. Often both functions are combined in a set of linkages.

Examples of location linkages include:

- Satchell link
- Panhard rod
- Watt's linkage
- WOBLink
- Mumford linkage
- Leaf springs used for location (transverse or longitudinal)
 - Fully elliptical springs usually need supplementary location links and are no longer in common use
 - Longitudinal semi-elliptical springs used to be common and still are used in heavy-duty trucks and aircraft. They have the advantage that the spring rate can easily be made progressive (non-linear).
 - A single transverse leaf spring for both front wheels and/or both back wheels, supporting solid axles, was used by Ford Motor Company, before and soon after World War II, even on expensive models. It had the advantages of simplicity and low unsprung weight (compared to other solid axle designs).

In a front engine, rear-drive vehicle, dependent rear suspension is either "live axle" or deDion axle, depending on whether or not the differential is carried on the axle. Live axle is simpler but the unsprung weight contributes to wheel bounce.

Because it assures constant camber, dependent (and semi-independent) suspension is most common on vehicles that need to carry large loads as a proportion of the vehicle weight, that have relatively soft springs and that do not (for cost and simplicity reasons)

use active suspensions. The use of dependent front suspension has become limited to heavier commercial vehicles.



A rear independent suspension on an AWD car.

Semi-independent suspension

In a semi-independent suspensions, the wheels of an axle are able to move relative to one another as in an independent suspension but the position of one wheel has an effect on the position and attitude of the other wheel. This effect is achieved via the twisting or deflecting of suspension parts under load. The most common type of semi-independent suspension is the twist beam.

- Twist beam

Independent suspension

The variety of independent systems is greater and includes:

- Swing axle
- Sliding pillar
- MacPherson strut/Chapman strut
- Upper and lower A-arm (double wishbone)

- multi-link suspension
- semi-trailing arm suspension
- swinging arm
- leaf springs
 - Transverse leaf springs when used as a suspension link, or four quarter elliptics on one end of a car are similar to wishbones in geometry, but are more compliant. Examples are the front of the original Fiat 500, the Panhard Dyna Z and the early examples of Peugeot 403 and the back of the AC Ace and AC Aceca.

Because the wheels are not constrained to remain perpendicular to a flat road surface in turning, braking and varying load conditions, control of the wheel camber is an important issue. Swinging arm was common in small cars that were sprung softly and could carry large loads, because the camber is independent of load. Some active and semi-active suspensions maintain the ride height, and therefore the camber, independent of load. In sports cars, optimal camber change when turning is more important.

Wishbone and multi-link allow the engineer more control over the geometry, to arrive at the best compromise, than swing axle, MacPherson strut or swinging arm do; however the cost and space requirements may be greater. Semi-trailing arm is in between, being a variable compromise between the geometries of swinging arm and swing axle.

Armoured fighting vehicle suspension



This Grant I tank's suspension has road wheels mounted on wheel trucks, or *bogies*.

Military AFVs, including tanks, have specialized suspension requirements. They can weigh more than seventy tons and are required to move at high speed over very rough ground. Their suspension components must be protected from land mines and antitank weapons. Tracked AFVs can have as many as nine road wheels on each side. Many wheeled AFVs have six or eight wheels, to help them ride over rough and soft ground.

The earliest tanks of World War I had fixed suspension with no movement whatsoever. This unsatisfactory situation was improved with leaf spring or coil spring suspensions adopted from agricultural, automotive or railway machinery, but even these had very limited travel.

Speeds increased due to more powerful engines, and the quality of ride had to be improved. In the 1930s, the Christie suspension was developed, which allowed the use of coil springs inside a vehicle's armored hull, by changing the direction of force deforming the spring, using a bell crank. Horstmann suspension was a variation which used a combination of bell crank and exterior coil springs, in use from the 1930s to the 1990s.

By World War II the other common type was torsion-bar suspension, getting spring force from twisting bars inside the hull — this had less travel than the Christie-type, but was significantly more compact, allowing more space inside the hull, with consequent possibility to install larger turret rings and thus a heavier main armament. The torsion-bar suspension, sometimes including shock absorbers, has been the dominant heavy armored vehicle suspension since World War II.

Chapter 2

Sway Bar and Axle

Sway bar



Sway bar (in black) in the rear axle of a Porsche

A **sway bar** or **anti-roll bar** forms part of an automobile suspension. It connects opposite (left/right) wheels together through short lever arms linked by a torsion spring. A sway bar increases the suspension's roll stiffness—its resistance to roll in turns, independent of its spring rate in the vertical direction. The first stabilizer bar patent was awarded to the Canadian S. L. C. Coleman of Fredericton, New Brunswick on April 22, 1919.

Principles

A sway bar is usually a torsion spring that resists body roll motions. It is usually constructed out of a U-shaped steel bar that connects to the body at two points, and at the left and right sides of the suspension. If the left and right wheels move together, the bar

rotates about its mounting points. If the wheels move relative to each other, the bar is subjected to torsion and forced to twist.

The bar resists the torsion through its stiffness. The stiffness of an anti-roll bar is based on the fourth power of its radius, the stiffness of the material, the inverse of the length of the lever arms (i.e., the shorter the lever arm, the stiffer the bar), the geometry of the mounting points, and the rigidity of the bar's mounting points. The stiffer the bar, the more force required to move the left and right wheels relative to each other. This increases the amount of force required to make the body roll.

In a turn, the sprung mass of the vehicle's body produces a lateral force at the centre of gravity (CG), proportional to lateral acceleration. Because the CG is usually not on the roll axis, the lateral force creates a moment about the roll axis that tends to roll the body. (The roll axis is a line that joins the front and rear roll centers (SAEJ670e)). The moment is called the roll couple.

Roll couple is resisted by the suspension roll stiffness, which is a function of the spring rate of the vehicle's springs and of the anti-roll bars, if any. The use of anti-roll bars allows designers to reduce roll without making the suspension's springs stiffer in the vertical plane, which allows improved body control with less compromise of ride quality.

One effect of body (frame) lean, for typical suspension geometry, is positive camber of the wheels on the outside of the turn and negative on the inside, which reduces their cornering grip (especially with cross ply tires).

Main functions

Anti-roll bars provide two main functions. The first function is the reduction of body lean. The reduction of body lean is dependent on the total roll stiffness of the vehicle. Increasing the total roll stiffness of a vehicle does not change the steady state total load (weight) transfer from the inside wheels to the outside wheels, it only reduces body lean. The total lateral load transfer is determined by the CG height and track width.

The other function of anti-roll bars is to tune the handling balance of a car. Understeer or oversteer behavior can be tuned out by changing the proportion of the total roll stiffness that comes from the front and rear axles. Increasing the proportion of roll stiffness at the front will increase the proportion of the total load transfer that the front axle reacts and decrease the proportion that the rear axle reacts. This will cause the outer front wheel to run at a comparatively higher slip angle, and the outer rear wheel to run at a comparatively lower slip angle, which is an understeer effect. Increasing the proportion of roll stiffness at the rear axle will have the opposite effect and decrease understeer.

Drawbacks

Because an anti-roll bar connects wheels on the opposite sides of the vehicle together, the bar will transmit the force of one-wheel bumps to the opposite wheel. On rough or broken

pavement, anti-roll bars can produce jarring, side-to-side body motions (a "waddling" sensation), which increase in severity with the diameter and stiffness of the sway bars. Excessive roll stiffness, typically achieved by configuring an anti-roll bar too aggressively, will cause the inside wheels to lift off the ground during very hard cornering. This, of course, is only possible if the regular spring rate actually allows the outside wheels to handle the much increased load. This can be used to advantage: many front wheel drive production cars will lift a wheel when cornering hard, in order to overload the other wheel on the axle, so limiting understeer.

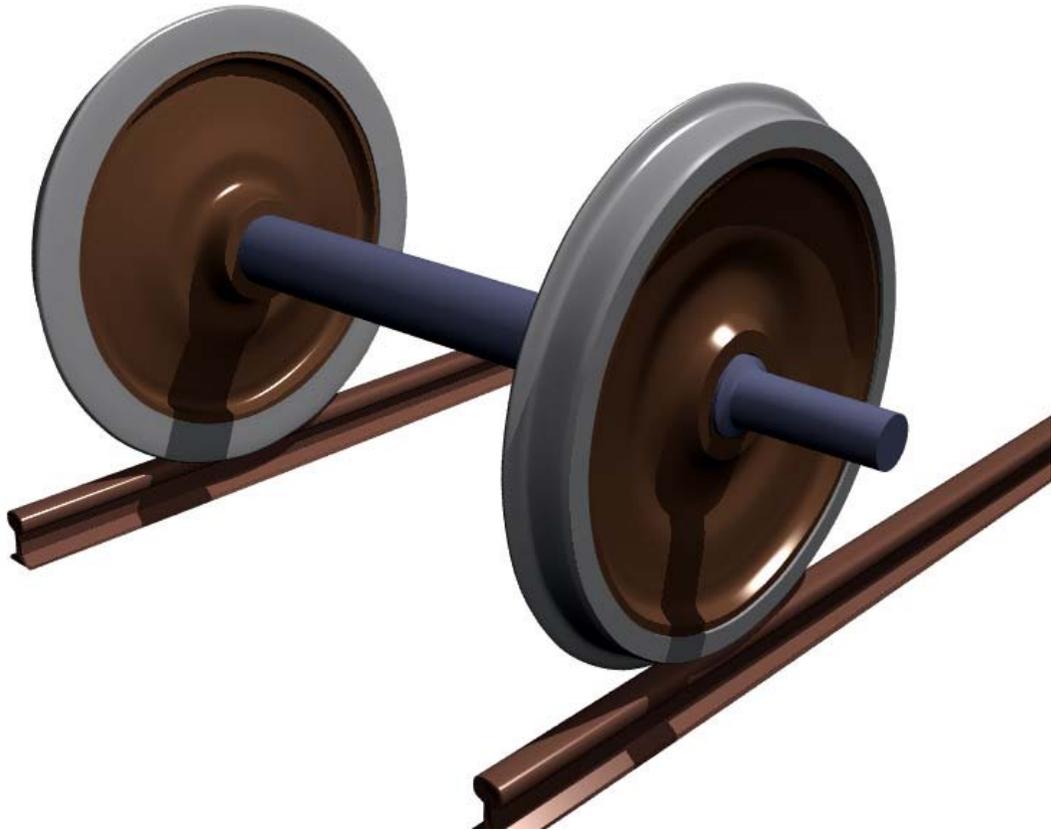
Adjustable bars

Some anti-roll bars, particularly those intended for use in auto racing, are externally adjustable while the car is in the pit whereas some systems can be adjusted in real time by the driver from inside the car, such as in JGTC. This allows the stiffness to be altered by increasing or reducing the length of the lever arms. This permits the roll stiffness to be tuned for different situations without replacing the entire bar.

Active systems

Some high-priced cars, such as the Range Rover Sport and BMW 7-series, have begun to use "active" anti-roll bars that can be proportionally controlled automatically by a suspension-control computer, reducing body lean in turns while improving rough-road ride quality. The first to use this was the Citroen Xantia Activa, a medium sized sedan sold in Europe. The Activa system featured an anti-roll bar that could be stiffened under the command of the suspension ECU during hard cornering. The car rolled at any time at most 2 degrees. Mercedes S-class ABC system uses another approach: the computer uses sensors to detect lateral load, lateral force, and height difference in the suspension strut, then uses hydraulic pressure to raise or lower the spring to counter roll. This system removes the anti-roll bar. Most active roll control systems allow a small degree of roll to give a more natural feel.

Axle



Train wheels are affixed to a straight axle, such that both wheels rotate in unison. This is called a wheelset.

An **axle** is a central shaft for a rotating wheel or gear. On wheeled vehicles, the axle may be fixed to the wheels, rotating with them, or fixed to its surroundings, with the wheels rotating around the axle. In the former case, bearings or bushings are provided at the mounting points where the axle is supported. In the latter case, a bearing or bushing sits inside the hole in the wheel to allow the wheel or gear to rotate around the axle. Sometimes, especially on bicycles, the latter type is referred to as a spindle.

On cars and trucks, several senses of the word "axle" co-occur in casual usage, referring to the shaft itself, its housing, or simply any transverse pair of wheels. The shaft itself rotates with the wheel, being either bolted or splined in fixed relation to it, and is called an "axle" or "axle shaft". However, it is equally true that the housing around it (typically a casting) is also called an "axle" (or "axle housing"). An even broader (somewhat figurative) sense of the word refers to every transverse pair of wheels, whether they are

connected to each other or not. Thus even transverse pairs of wheels in an independent suspension are usually called "an axle".

Vehicle axles

Axles are an integral component of a wheeled vehicle. In a live-axle suspension system, the axles serve to transmit driving torque to the wheel, as well as to maintain the position of the wheels relative to each other and to the vehicle body. The axles in this system must also bear the weight of the vehicle plus any cargo. A non-driving axle, such as the front beam axle in Heavy duty trucks and some 2 wheel drive light trucks and vans, will have no shaft. It serves only as a suspension and steering component. Conversely, many front wheel drive cars have a solid rear beam axle.

In other types of suspension systems, the axles serve only to transmit driving torque to the wheels; The position and angle of the wheel hubs is a function of the suspension system. This is typical of the independent suspension found on most newer cars and SUV's, and on the front of many light trucks. These systems still have a differential, but it will not have attached axle housing tubes. It may be attached to the vehicle frame or body, or integral in a transaxle. The axle shafts (usually C.V. type) then transmit driving torque to the wheels. Like a full floating axle system, the shafts in an independent suspension system do not support and vehicle weight.

"Axle" in reference to a vehicle also has a more ambiguous definition, meaning parallel wheels on opposing sides of the vehicle, regardless of their mechanical connection type to each other and the vehicle frame or body.

Structural features



0 Series Shinkansen Wheel

A straight axle is a single rigid shaft connecting a wheel on the left side of the vehicle to a wheel on the right side. The axis of rotation fixed by the axle is common to both wheels. Such a design can keep the wheel positions steady under heavy stress, and can therefore support heavy loads. Straight axles are used on trains, for the rear axles of commercial trucks, and on heavy duty off-road vehicles. The axle can be protected and further reinforced by enclosing the length of the axle in a housing.

In split-axle designs, the wheel on each side is attached to a separate shaft. Modern passenger cars have split drive axles. In some designs, this allows independent suspension of the left and right wheels, and therefore a smoother ride. Even when the suspension is not independent, split axles permit the use of a differential, allowing the left and right drive wheels to be driven at different speeds as the automobile turns, improving traction and extending tire life.

A tandem axle is a group of two or more axles situated close together. Trucks designs will use such a configuration to provide a greater weight capacity than a single axle. Semi trailers usually have a tandem axle at the rear.

Drive axles



Splines on a front drive axle.

An axle that is driven by the engine is called a **drive axle**.

Modern front wheel drive cars typically combine the transmission and front axle into a single unit called a transaxle. The drive axle is a split axle with a differential and universal joints between the two half axles. Each half axle connects to the wheel by use of a constant velocity (CV) joint which allows the wheel assembly to move freely vertically as well as to pivot when making turns.

In rear wheel drive cars and trucks, the engine turns a driveshaft which transmits rotational force to a drive axle at the rear of the vehicle. The drive axle may be a live axle, but modern automobiles generally use a split axle with a differential.

Some simple vehicle designs, such as go-karts, may have a single driven wheel where the drive axle is a split axle with only one of the two shafts driven by the engine, or else have both wheels connected to one shaft without a differential.

Dead axles/lazy axles



This dump truck has an airlift pusher axle, shown in the raised position.

A **dead axle**, also called **lazy axle**, is not part of the drivetrain but is instead free-rotating. The rear axle of a front-wheel drive car may be considered a dead axle. Many trucks and trailers use dead axles for strictly load-bearing purposes. A dead axle located immediately in front of a drive axle is called a **pusher axle**. A **tag axle** is a dead axle situated behind a drive axle. On some vehicles (such as motorcoaches), the tag axle may be steerable.

Some dump trucks and trailers are configured with **lift axles** (also known as airlift axles or drop axles), which may be mechanically raised or lowered. The axle is lowered to increase the weight capacity, or to distribute the weight of the cargo over more wheels, for example to cross a weight restricted bridge. When not needed, the axle is lifted off the ground to save wear on the tires and axle and to increase traction in the remaining wheels. Lifting an axle also makes the vehicle perform better on tighter turns.

Several manufacturers offer computer-controlled airlift, so that the dead axles are automatically lowered when the main axle reaches its weight limit. The dead axles can still be lifted by the press of a button if needed.

Full-floating vs. semi-floating vs. Non-floating

The full-floating design is typically used in most 3/4 and 1-ton light trucks, medium duty trucks and heavy-duty trucks, as well as most agricultural applications, such as large tractors and combines. There are a few exceptions, such as many Land-Rover vehicles. A full-floating axle can be identified by a protruding hub to which the axle shaft flange is bolted. These axles are able to carry more weight than a semi-floating or non-floating axle assembly because the hubs have two bearings riding on a fixed spindle. The axle shafts themselves do not carry any weight; they serve only to transmit torque from the

differential to the wheels. Full-floating axle shafts are retained by the aforementioned flange bolted to the hub, while the hub and bearings are retained on the spindle by a large nut.

The semi-floating and non-floating design carry the weight of the vehicle on the axle shaft itself; there is a single bearing at the end of the axle housing that carries the load from the axle and that the axle rotates through. With a semi-floating axle, the axles themselves serve as the inner bearing race and are retained by c-clips that are in the differential carrier. Non-floating axles have the bearings (with inner races) pressed onto the axle shaft (usually accompanied by a snap-ring), and are retained by a plate that bolts to a flange on the axle housing. Both of these designs are found under most 1/2 ton and lighter trucks and SUV's, and rear or all-wheel drive cars with live axle suspension, though the non-floating type all but disappeared in American cars and trucks during the late 1970's.

Chapter 3

Beam Axle and Camber Angle

Beam axle



Solid axle and Panhard rod on a 2002 Mazda MPV

A **beam axle** is a suspension system, also called a **solid axle**, in which one set of wheels is connected laterally by a single beam or shaft. A live axle is a type of beam axle in which the shaft (or shafts, since live axles, while connected to move as a single unit, are seldom one piece) also transmits power to the wheels; a beam axle that does not also transmit power is sometimes called a **dead axle**. Beam axles are commonly used at the rear wheels of a vehicle, but historically they have also been used as front axles in rear wheel drive cars. Ford used beam axles across the range until 1949, only being phased out in Europe as recently as the early 1960s with the Ford Popular being suspended (though the 100E was fitted with MacPherson struts).

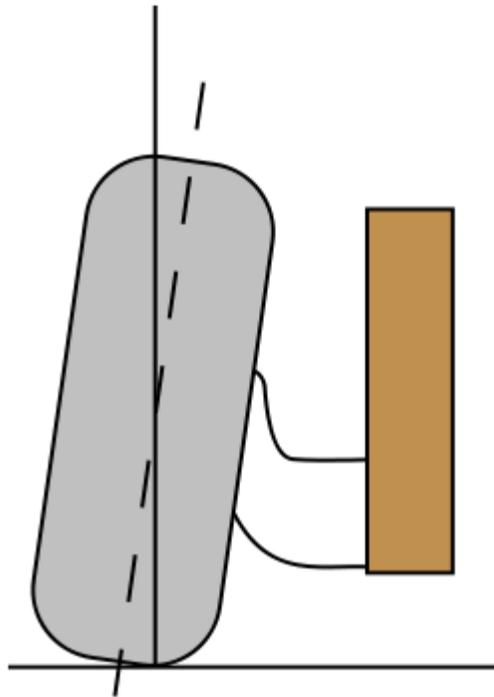
Beam axles are typically suspended either by leaf springs or coil springs. In some cases, a Panhard rod or similar device may be used to control the lateral motion of the axle.

A similar suspension is the Twist-beam rear suspension, in which the beam axle also functions as an anti-roll bar to control the roll motion of the body.

The principal advantage of the beam axle is that it is simple and cheap to manufacture. It also engages little or no interior volume within the vehicle. Its drawbacks are that it does not allow each wheel to move independently in response to bumps, and the mass of the beam is part of the unsprung weight of the vehicle, which can further reduce ride quality.

Because beam axles do not ever exhibit any camber change as the suspension travels, they are ideal for carrying heavy or varying loads. Although this negatively impacts cornering compared to other suspension designs (because the wheels have zero camber gain during body roll), beam axles are nearly universally used in heavy-duty trucks. One notable exception is the Czech manufacturer Tatra, who instead use swing-axles in conjunction with a central 'backbone' chassis. Most light and medium duty pickup trucks and vans also use a beam axle, at least in the rear.

Camber angle



From the front of the car, a right wheel with a negative camber angle



The 1960 Milliken MX1 Camber Car showing a large negative camber.

Camber angle is the angle made by the wheels of a vehicle; specifically, it is the angle between the vertical axis of the wheels used for steering and the vertical axis of the vehicle when viewed from the front or rear. It is used in the design of steering and suspension. If the top of the wheel is farther out than the bottom (that is, away from the axle), it is called **positive camber**; if the bottom of the wheel is farther out than the top, it is called **negative camber**.

Camber angle alters the handling qualities of a particular suspension design; in particular, negative camber improves grip when cornering. This is because it places the tire at a more optimal angle to the road, transmitting the forces through the vertical plane of the tire, rather than through a shear force across it. Another reason for negative camber is that

a rubber tire tends to roll on itself while cornering. If the tire had zero camber, the inside edge of the contact patch would begin to lift off of the ground, thereby reducing the area of the contact patch. By applying negative camber, this effect is reduced, thereby maximizing the contact patch area. Note that this is only true for the outside tire during the turn; the inside tire would benefit most from positive camber.

On the other hand, for maximum straight-line acceleration, the greatest traction will be attained when the camber angle is zero and the tread is flat on the road. Proper management of camber angle is a major factor in suspension design, and must incorporate not only idealized geometric models, but also real-life behavior of the components; flex, distortion, elasticity, etc. What was once an art has now become much more scientific with the use of computers, which can optimize all of the variables mathematically instead of relying on the designer's intuitive feel and experience. As a result, the handling of even low-priced automobiles has improved dramatically in recent years.

In cars with double wishbone suspensions, camber angle may be fixed or adjustable, but in MacPherson strut suspensions, it is normally fixed. The elimination of an available camber adjustment may reduce maintenance requirements, but if the car is lowered by use of shortened springs, the camber angle will change. Excessive camber angle can lead to increased tire wear and impaired handling. Significant suspension modifications may correspondingly require that the upper control arm or strut mounting points be altered to allow for some inward or outward movement, relative to longitudinal centerline of the vehicle, for camber adjustment. Aftermarket plates with slots for strut mounts instead of just holes are available for most of the commonly modified models of cars.

Off-road vehicles such as agricultural tractors generally use positive camber. In such vehicles, the positive camber angle helps to achieve a lower steering effort. Also, some single-engined general aviation aircraft that are primarily meant to operate from unimproved surfaces, such as bush planes and cropdusters, have their taildragger gear's main wheels equipped with positive-cambered main wheels to better handle the deflection of the landing gear, as the aircraft settles on rough, unpaved airstrips.

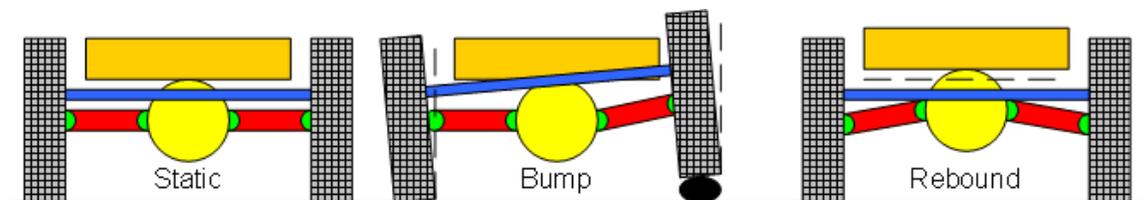
Road camber

In roads, an **adverse camber** refers to any road that tilts on the same side that a vehicle leans to on a road. The term camber or cant refers to the way in which a road slopes from its centre. Usually on a right hand bend the road would slope downwards from left to right; this is known as a **crossfall camber** or cross slope — the opposite to an adverse camber.

Chapter 4

De Dion Tube and Double Wishbone Suspension

De Dion tube



de Dion suspension characteristics: Camber change on bumps, none on rebound. de Dion tube is shown in blue. The differential (yellow) is connected directly to the chassis (orange).

A **de Dion tube** is an automobile suspension technology. It is a sophisticated form of non-independent suspension and is a considerable improvement over the alternative swing axle and Hotchkiss drive types. A de Dion suspension uses universal joints at both the wheel hubs and differential, and uses a solid tubular beam to hold the opposite wheels in parallel. Unlike an anti-roll bar, a de Dion tube is not directly connected to the chassis nor is it intended to flex. In suspension geometry it is close to the trailing beam suspension seen on many front wheel drive cars, but without the torsional flexibility of that suspension.

History

The de Dion tube was named after Comte Jules-Albert de Dion, founder of French automobile manufacturer De Dion-Bouton. The tube, however, was invented around 1894 by co-founder Charles Trépardoux for use on the company's steam tricycles.

Advantages and disadvantages

The benefits of a de Dion suspension include:

1. Reduced unsprung weight compared to the Hotchkiss drive since the differential is connected to the chassis.
2. Unlike a fully independent suspension there are no camber changes on suspension unloading (or rebound). Fixing the camber of both wheels at 0° assists in obtaining good traction from wide tires and also tends to reduce wheel hop under high power operations compared to an independent suspension.

There are costs, however:

1. A pair of CV or universal joints are required for each wheel, adding complexity and weight.
2. If coil springs are used then a lateral location link (usually either a Panhard rod or Watt's linkage), plus additional torque links on each side (five link suspension) or a combination of lower trailing links and an upper transverse wishbone are required. None of these additional links are required if leaf springs are used.
3. Sympathetic camber changes on opposite wheels are seen on single-wheel suspension compression. This is not important for operation on improved surfaces but is more critical for rough road or off road use.
4. Compared to a fully independent rear suspension the ability to refine the dynamic response of the vehicle is somewhat limited.

Use in production cars



de Dion tube used in a 1998 Ford Ranger EV

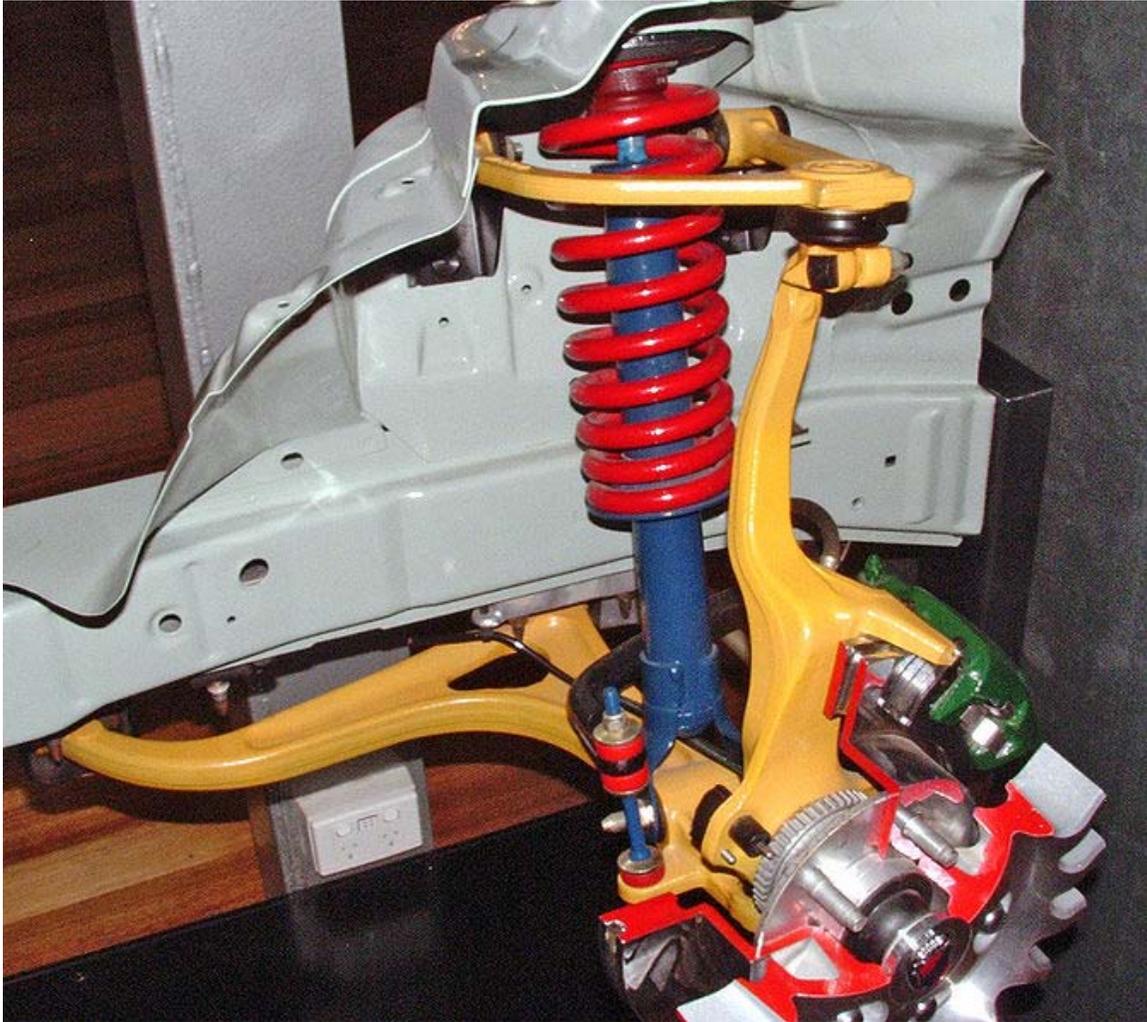
Older cars

In addition the original Mazda Cosmo, Alfa Romeo Alfetta, GTV6, Giulietta, Alfa 6, 90, 75/Milano, Lancia Aurelia (fourth series onwards), first and second generation Prince Gloria, Lancia Flaminia, Volvo 300-series, Rover P6 and Dodge Caravan & Grand Caravan (all wheel drive version from 1991–2004) are examples of production vehicles using this suspension. Some of the largest Opels, such as the Opel Diplomat "B" of 1969, all Aston Martins from 1967 to 1989, Ferrari 375 and 250TR, Maserati Quattroporte, Bugatti 251, Mercedes-Benz W125 and W154 as well as Auto Union Type D also used this suspension.

Recent cars

The Smart Fortwo and Smart Roadster micro-compact cars produced by DaimlerChrysler, Mitsubishi i kei car produced by Mitsubishi Motors and the Caterham 7 (a development of the Lotus Seven after Lotus sold the design rights to Caterham Cars), are the only cars currently in production that utilize this arrangement, as well as the products of some kit car companies. A recent vehicle to use this suspension coupled with leaf springs was the Ford Ranger EV. The American built MV-1 van by VPG also uses this suspension in the rear with leaf springs and is just starting production in spring 2010.

Double wishbone suspension



Wishbones and upright painted yellow

In automobiles, a **double wishbone** (or **upper and lower A-arm**) **suspension** is an independent suspension design using two (occasionally parallel) wishbone-shaped arms to locate the wheel. Each wishbone or arm has two mounting points to the chassis and one joint at the knuckle. The shock absorber and coil spring mount to the wishbones to control vertical movement. Double wishbone designs allow the engineer to carefully control the motion of the wheel throughout suspension travel, controlling such parameters as camber angle, caster angle, toe pattern, roll center height, scrub radius, scuff and more.

Implementation



Double Wishbone Suspension

The double wishbone suspension can also be referred to as double 'A' arms, and short long arm (SLA) suspension if the upper and lower arms are of unequal length. A single wishbone or A-arm can also be used in various other suspension types, such as MacPherson strut and Chapman strut. The upper arm is usually shorter to induce negative camber as the suspension jounces (rises). When the vehicle is in a turn, body roll results in positive camber gain on the inside wheel. The outside wheel also jounces and gains negative camber due to the shorter upper arm. The suspension designer attempts to balance these two effects to cancel out and keep the tire perpendicular to the ground. This is especially important for the outer tire because of the weight transfer to this tire during a turn.

Between the outboard end of the arms is a knuckle with a spindle (the kingpin), hub, or upright which carries the wheel bearing and wheel. Knuckles with an integral spindle usually do not allow the wheel to be driven. A bolt on hub design is commonly used if the wheel is to be driven.

In order to resist fore-aft loads such as acceleration and braking, the arms need two bushings or ball joints at the body.

At the knuckle end, single ball joints are typically used, in which case the steering loads have to be taken via a steering arm, and the wishbones look A- or L-shaped. An L-shaped arm is generally preferred on passenger vehicles because it allows a better compromise of handling and comfort to be tuned in. The bushing in line with the wheel can be kept relatively stiff to effectively handle cornering loads while the off-line joint can be softer to allow the wheel to recess under fore aft impact loads. For a rear suspension, a pair of joints can be used at both ends of the arm, making them more H-shaped in plan view. Alternatively, a fixed-length driveshaft can perform the function of a wishbone as long as the shape of the other wishbone provides control of the upright. This arrangement has been successfully used in the Jaguar IRS. In elevation view, the suspension is a 4-bar link, and it is easy to work out the camber gain and other parameters for a given set of bushing or ball joint locations. The various bushings or ball joints do not have to be on horizontal axes, parallel to the vehicle centre line. If they are set at an angle, then antidive and antisquat can be dialed in.

Advantages & Disadvantages

The advantage of a double wishbone suspension is that it is fairly easy to work out the effect of moving each joint, so you can tune the kinematics of the suspension easily and optimize wheel motion. It is also easy to work out the loads that different parts will be subjected to which allows more optimized lightweight parts to be designed. They also provide increasing negative camber gain all the way to full jounce travel unlike the MacPherson strut which provides negative camber gain only at the beginning of jounce travel and then reverses into positive camber gain at high jounce amounts.

The disadvantage is that it is slightly more complex than other systems like a MacPherson strut. Due to the increased number of components within the suspension setup it takes much longer to service and is heavier than an equivalent MacPherson design.

Uses

The double wishbone suspension was introduced in 1935 by Packard Motor Car Company of Detroit, Michigan on the Packard One-Twenty, and advertised as a safety feature. Prior to the dominance of front wheel drive in the 1980s, many everyday cars used double wishbone front-suspension systems, or a variation on it. Since that time, the MacPherson strut has become almost ubiquitous, as it is simpler and cheaper to manufacture. In most cases, a MacPherson strut requires less space to engineer into a

chassis design, and in front-wheel-drive layouts, can allow for more room in the engine bay. A good example of this is observed in the Honda Civic, which changed its front-suspension design from a double wishbone design to a MacPherson strut design after the year 2000 model.

Double wishbones are usually considered to have superior dynamic characteristics as well as load-handling capabilities, and are still found on higher performance vehicles. Examples of makes in which double wishbones can be found include Alfa Romeo, Honda and Mercedes-Benz. Short long arms suspension, a type of double wishbone suspension, is very common on front suspensions for medium-to-large cars such as the Honda Accord, Peugeot 407, or Mazda 6/Atenza, and is very common on sports cars and racing cars.

Chapter 5

Hydrolastic and Independent Suspension

Hydrolastic

Hydrolastic is a type of space-efficient automotive suspension system used in many cars produced by British Motor Corporation (BMC) and its successor companies.

Invented by famous British rubber engineer Alex Moulton, and first used on the 1962 BMC project ADO16 under designer Alec Issigonis (of Mini fame), later to be launched as the Morris 1100.

Description

The system replaces the separate springs and dampers of a conventional suspension system with integrated, space efficient, fluid filled, displacer units, which are interconnected between the front and rear wheels on each side of the vehicle. The official recipe for genuine BMC/MG Rover fluid is as follows:

- 49% alcohol
- 49% distilled water
- 1% triethanolamine phosphate
- 1% sodium mercaptobenzothiazole

Although the official recipe contains triethanolamine phosphate and sodium mercaptobenzothiazole, many home mechanics refill the system without these two ingredients, and uses only alcohol (methylated spirits) and concentrated glycol antifreeze in a 50/50 ratio.

Each displacer unit contains a rubber spring, and damping is achieved by the displaced fluid passing through rubber valves. The displaced fluid passes to the displacer of the

paired wheel, thus providing a dynamic interaction between front and rear wheels. When a front wheel encounters a bump fluid is transferred to the corresponding rear displacer then lowers the rear wheel, hence lifting the rear, minimising pitch associated with the bump. Naturally the reverse occurs when it is a rear wheel that encounters a bump. This effect is particularly good on small cars as small wheelbase vehicles are more affected by pitching than long wheelbase vehicles.

Servicing difficulties

The system was not popular with home mechanics, as it had to be re-pressurized after a chassis or subframe replacement. Even welding the sub-frame to repair rust damage typically required the system to be drained. The only way to re-pressurize was to pay a properly equipped mechanic, usually at a BMC dealer. Inevitably the charge for this service was higher than many cared to pay.

Influences

Jon Pressnell suggests in his book that the hydropneumatic suspension of the Citroën DS motivated Issigonis and Moulton, who were at the time of the launch of the DS working on a rubber and fluid suspension system themselves. Pressnell also suggests that the complexity of the Citroën system encouraged Moulton to develop a much simpler system.

In a magazine interview for 'CAR' magazine in the late 1980s, Dr Moulton stated that he and Issigonis had also studied the Citroën 2CV in the 1950s, which featured fore/aft interconnected steel springs. They particularly wished to address the comical lack of roll stiffness of that car with the system that they were designing.

Hydragas

Hydragas is a type of automotive suspension system used in many cars produced by British Leyland and its successor companies.

Invented by British automotive engineer Alex Moulton, Hydragas is an evolution of the previous Hydrolastic system. It was first introduced in 1973 in the Austin Allegro and was later fitted to the 1975 Princess and its successor, the 1982 Austin Ambassador. Both systems attempt to address the ride-handling compromise of car suspension by interconnecting the suspension of the front and rear of the car in some way. Hydragas attempted to perform the same function and advantages as the hydropneumatic system developed by Citroën, but without its attendant complexity.

The heart of the system are the displacer units, which are pressurised spheres containing nitrogen gas. These replace the conventional steel springs of a regular suspension design. The means for pressurising the gas in the displacers is done by pre-pressurising a hydraulic fluid, and then connecting the displacer to its neighbour on the other axle. This

is unlike the Citroën system, which uses hydraulic fluid continuously pressurised by an engine-driven pump and regulated by a central pressure vessel.

Despite early problems (the Allegro version of Hydragas was found seriously wanting), it was gradually developed into an effective and efficient alternative to steel springs on later BL/Rover Group models such as the Austin Metro and MGF.

The Austin Maxi was the only in production car to feature both systems.. The Maxi featured 1100 designed Hydrolastic Units with the regulator valve fitted with the interconnection pipe. However in 1978 production of Hydrolastic bottles at Dunlop came to an end and BL modified the Leyland Princess Hydrogas bottles to fit. This involved fitting a new front subframe design, with a larger diameter horizontal chamber in the subframe.

Cars

Cars using the Hydrolastic suspension system:

- BMC 1100
- Mini (from 1964 to 1971)
- Austin America (from 1968 to 1971)
- Austin 1800
- Austin Maxi(Until March 1978)
- Austin 3-Litre
- MG 1100 (from 1962 to 1968)
- Morris 1500
- Huffaker Indianapolis cars 1964-1969 "MG Liquid Suspension Special"
- Wolseley Hornet
- Riley Elf
- Riley Kestrel
- Wolseley 1100
- Wolseley Six

Cars using the Hydragas suspension system:

- Austin Ambassador
- Princess
- Austin Allegro
- Austin Maxi (From March 1978 onwards)
- Austin Metro
- Rover Metro
- Rover 100
- MGF

Independent suspension



A multi-link type rear independent suspension on an AWD car. The anti-roll bar has some yellow paint on it.

Independent suspension is a broad term for any automobile suspension system that allows each wheel on the same axle to move vertically (i.e. reacting to a bump in the road) independently of each other. This is contrasted with a beam axle, live axle or deDion axle system in which the wheels are linked—movement on one side affects the wheel on the other side. Note that “independent” refers to the motion or path of movement of the wheels/suspension. It is common for the left and right sides of the suspension to be connected with anti-roll bars or other such mechanisms. The anti-roll bar ties the left and right suspension spring rates together but does not tie their motion together.

Most modern vehicles have **independent front suspension (IFS)**. Many vehicles also have an **independent rear suspension (IRS)**. IRS, as the name implies, has the rear wheels independently sprung. A **fully independent suspension** has an independent suspension on all wheels. Some early independent systems used swing axles, but modern systems use Chapman or MacPherson struts, trailing arms, multilink, or wishbones.

Independent suspension typically offers better ride quality and handling characteristics, due to lower *unsprung weight* and the ability of each wheel to address the road undisturbed by activities of the other wheel on the vehicle. Independent suspension requires additional engineering effort and expense in development versus a beam or live axle arrangement. A very complex *IRS* solution can also result in higher manufacturing costs.

The key reason for lower unsprung weight relative to a live axle design is that, for driven wheels, the differential unit does not form part of the unsprung elements of the suspension system. Instead it is either bolted directly to the vehicle's chassis or more commonly to a subframe.

The relative movement between the wheels and the differential is achieved through the use of swinging driveshafts connected via universal (U) joints, analogous to the constant-velocity (CV) joints used in front wheel drive vehicles.

Chapter 6

Hydropneumatic Suspension



Citroën suspension sphere

Hydropneumatic is a type of automotive suspension system, invented by Citroën, and fitted to Citroën cars, as well as being used under licence by other car manufacturers, notably Rolls-Royce, and Peugeot. It was also used on Berliet trucks. Similar systems are

also used on some military vehicles. The suspension was referred to as *oléopneumatique* in early literature, pointing to oil and air as its main components.

The purpose of this system is to provide a soft, comfortable, yet well-controlled ride quality. Its nitrogen springing medium is approximately six times more flexible than conventional steel, so self-leveling is incorporated to allow the vehicle to cope with the extraordinary suppleness provided. France was noted for poor road quality in the post-war years, so the only way to maintain relatively high speed in a vehicle was if it could easily absorb road irregularities.

While the system has inherent advantages over steel springs, generally recognized in the auto industry, it also has a perceived element of complexity, so automakers like Mercedes-Benz, British Leyland (Hydrolastic, Hydragas), and Lincoln (Air suspension) have sought to create simpler variants. The system had one key negative impact on the inventor, Citroën, only specialist garages were qualified to work on the cars, making them seem radically different from ordinary cars with common mechanicals.

This system uses a belt or camshaft driven pump from the engine to pressurise a special hydraulic fluid, which then powers the brakes, suspension and power steering. It can also power any number of features such as the clutch, turning headlamps and even power windows. The suspension system usually features driver-variable ride height, to provide extra clearance in rough terrain.

There have been many improvements to this system over the years, including variable ride firmness (Hydractive) and active control of body roll (Citroën Activa). The latest incarnation features a simplified single pump-accumulator sphere combination. Auto manufacturers are still trying to catch up with the combination of features offered by this 1954 suspension system, typically by adding layers of complexity to an ordinary steel spring mechanical system.

History



1954 Citroën Traction Avant 15CVH - high position

Citroën first introduced this system in 1954 on the rear suspension of the Traction Avant. The first full implementation was in the advanced DS in 1955. Major milestones of the hydropneumatics design were:

- During World War II, Paul Magès, an employee of Citroën, with no formal training in engineering, secretly develops the concept of an oil and air suspension to combine a new level of softness with vehicle control and self-levelling
- 1954 Traction Avant 15H: Rear suspension, using LHS hydraulic fluid.
- 1955 Citroën DS: Suspension, power steering, brakes and gearbox/clutch assembly powered by high pressure hydraulic assistance. A belt driven 7-piston pump, similar in size to a power steering pump, generates this pressure when the engine is running.
- 1962 Morris Motor Company introduces the BMC ADO16 ('1100') with hydrolastic suspension
- 1964 Mercedes-Benz introduces the 600 with air suspension designed to avoid Citroën patents
- 1965 Rolls-Royce licenses Citroën technology for the suspension of the new Silver Shadow
- 1966 Mercedes-Benz introduces the 6.3 also with air suspension

- 1967 The superior LHM mineral fluid is introduced
- 1970 Citroën GS: Adaptation of the hydropneumatic suspension to a small car
- 1970 Citroën SM: Variable speed auto-returning power steering, dubbed DIRAVI, and hydraulically actuated directional high beams
- 1974 The Mercedes-Benz 450SEL 6.9 becomes the first hydropneumatic Mercedes-Benz automobile, with the pump driven by the engine's timing chain instead of an external belt. This adaptation was used only for the suspension. Power steering and brakes were conventional hydraulic- and vacuum-powered, respectively.
- 1983 Citroën BX, built as a 4WD in 1990
- 1989 Citroën XM: Hydractive Suspension, electronic regulation of the hydropneumatic system; sensors measure acceleration and other factors
- 1990 Peugeot 405 Mi16x4: first Peugeot equipped with rear hydropneumatic suspension
- 1990 JCB Fastrac high speed agricultural tractor uses this system for its rear suspension.
- 1993 Citroën Xantia: Optional *Activa* (active suspension) system, eliminating body roll by acting on torsion bars. A *Xantia Activa* was able to reach more than 1g lateral acceleration
- 2001 Citroën C5: Hydractive 3 removes the need for central hydraulic pressure generation; combined pump/sphere unit for the suspension only and with electric height adjustment sensors
- 2005 Citroën C6: An improved version of the C5 system known as Hydractive 3+ (also fitted to some C5 models)
- 2008 JCB Fastrac high speed 7000 series agricultural tractors now use this system for front and rear suspension.

Functioning

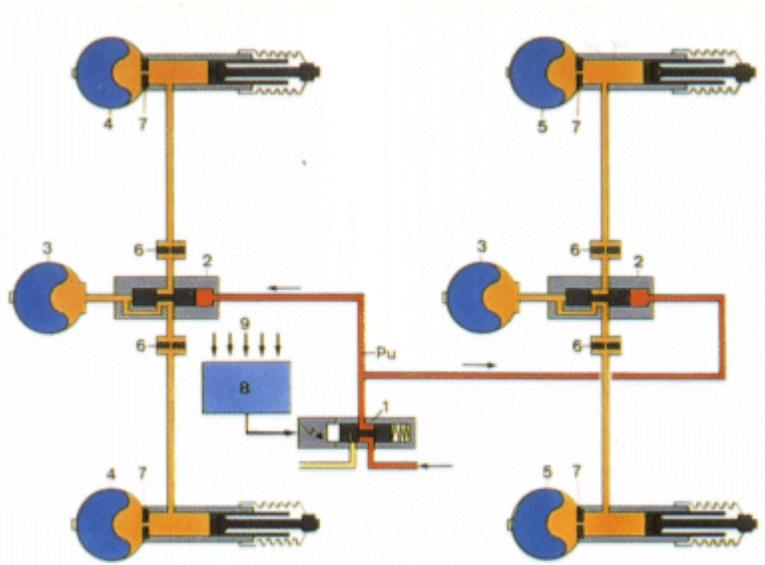


Diagram of the Hydractive system, showing centre spheres and stiffness valves

At the heart of the system, acting as pressure sink as well as suspension elements, are the so called spheres, five or six in all; one per wheel and one main accumulator as well as a dedicated brake accumulator on some models. On later cars fitted with Hydractive or Activa suspension, there may be as many as nine spheres. Spheres consist of a hollow metal ball, open to the bottom, with a flexible desmopan rubber membrane, fixed at the 'equator' inside, separating top and bottom. The top is filled with nitrogen at high pressure, up to 75 bar, the bottom connects to the car's hydraulic fluid circuit. The high pressure pump, powered by the engine, pressurizes the hydraulic fluid (LHM) and a accumulator sphere maintains a reserve of hydraulic power. This part of the circuit is at between 150 and 180 bars. It powers the front brakes first, prioritised via a security valve, and depending on type of vehicle, can power the steering, clutch, gear selector, etc.

Pressure flows from the hydraulic circuit to the suspension cylinders, pressurizing the bottom part of the spheres and suspension cylinders. Suspension works by means of a piston forcing LHM into the sphere, compacting the nitrogen in the upper part of the sphere; damping is provided by a two-way 'leaf valve' in the opening of the sphere. LHM has to squeeze back and forth through this valve which causes resistance and controls the suspension movements. It is the simplest damper and one of the most efficient. Ride height correction (self levelling) is achieved by height corrector valves connected to the anti-roll bar, front and rear. When the car is too low, the height corrector valve opens to allow more fluid into the suspension cylinder (e.g., the car is loaded). When the car is too high (e.g. after unloading) fluid is returned to the system reservoir via low-pressure return lines. Height correctors act with some delay in order not to correct regular suspension movements. The rear brakes are powered from the rear suspension circuit. Because the pressure there is proportional to the load, so is the braking power.

LHS versus LHM

Citroën quickly realized that standard brake fluid was not ideally suited to high pressure hydraulics, and developed a special red coloured hydraulic fluid named LHS, which they used from 1954 to 1967. The chief problem with LHS was that it absorbed water moisture and dust from the air which caused corrosion in the system. Most hydraulic brake systems are sealed from the outside air by a rubber diaphragm in the reservoir filler cap, but the Citroën system had to be vented to allow the fluid level in the reservoir to rise and fall, thus it was not hermetically sealed. Consequently, each time the suspension would rise, the fluid level in the reservoir dropped, drawing in fresh moisture-laden air. The large surface of the fluid in the reservoir readily absorbed moisture. Since the system recirculates fluid continually through the reservoir, all the fluid was repeatedly exposed to the air and its moisture content.



LHM reservoir and green suspension sphere in a Citroën Xantia

To overcome these shortcomings of LHS, Citroën developed a new green fluid, *LHM* (*Liquide Hydraulique Minéral*). LHM is a mineral oil, quite close to automatic transmission fluid. Mineral oil is not hygroscopic (i.e., it will not absorb water from the air), unlike standard brake fluid, so therefore gas bubbles do not form in the system, as would be the case with standard brake fluid, creating a 'spongy' brake feel. Use of mineral oil has thus spread beyond Citroën, Rolls-Royce, Peugeot, and Mercedes-Benz, to include Jaguar, Audi, and BMW.

LHM, being a mineral oil, absorbs only an infinitesimal proportion of moisture, plus it contains corrosion inhibitors. The dust inhalation problem continued, so a filter assembly was fitted into the hydraulic reservoir. Cleaning the filters and changing the fluid at the recommended intervals removes most dust and wear particles from the system, ensuring the longevity of the system. Failure to keep the oil clean is the main cause of problems. It is also imperative to always use the correct fluid for the system; the two types of fluids and their associated system components are not interchangeable. If the wrong type of fluid is used, the system must be drained and rinsed with Hydraflush, before draining again and filling with the correct fluid. These procedures are clearly described in DIY manuals obtainable from automotive retailers.

The latest Citroën cars with Hydractive 3 suspension have a new orange coloured *LDS* hydraulic fluid. This lasts longer and requires less frequent attention.

Manufacturing

The whole high pressure part of the system is manufactured from steel tubing of small diameter, connected to valve control units by Lockheed type pipe unions with special seals made from desmopan rubber, a type of rubber compatible with the LHM fluid. The moving parts of the system (e.g., suspension strut or steering ram) are sealed by contact seals between the cylinder and piston for tightness under pressure. The other plastic/rubber parts are return tubes from valves such as the brake control or height corrector valves, also catching seeping fluid around the suspension push-rods. Height corrector, brake master valve and steering valve spools, and hydraulic pump pistons have extremely small clearances (1–3 micrometres) with their cylinders, permitting only a very low leakage rate. The metal and alloy parts of the system rarely fail even after excessively high mileages but the rubber components (especially those exposed to the air) can harden and leak, typical failure points for the system.

Spheres are not subject to mechanical wear, but suffer pressure loss, due to the pressurised nitrogen diffusing through the membrane. They can, however, be recharged which is cheaper than replacing them. When Citroën designed their Hydractive 3 suspension they re-designed the spheres with new nylon membranes, which greatly slow the rate of deflation. These are recognisable by their grey colouring.

Older, green coloured, suspension spheres typically last between 60,000 and 100,000 km. Spheres once had a threaded plug on top for recharging. Newer spheres do not have this plug, but it can be retrofitted enabling them to be re-gassed. The sphere membrane has an indefinite life unless run at low pressure, which leads to rupture. Timely recharging, approximately every 3 years, is thus vital. A ruptured membrane means suspension loss at the attached wheel, however, ride height is unaffected. With no springing other than the (slight) flexibility of tyres, hitting a pothole with a flat sphere can bend the suspension parts or dent a wheel rim. In the case of main accumulator sphere failure, the high pressure pump is the only source of braking pressure for the front wheels. Some older cars had a separate front brake accumulator on power steering models.

The old LHS and LHS2 (coloured red) cars used a different rubber in the diaphragms and seals that is *not* compatible with green LHM. The orange LDS fluid in Hydractive cars is also incompatible with other fluids.

Advantages



Arjun Main battle tank uses hydro pneumatic suspension for better crew comfort and also for increased firing accuracy.

Hydropneumatics have a number of natural advantages over steel springs that are poorly understood, leading to general public perception that hydropneumatics are merely "good for comfort". They actually also have great advantages related to car handling and control efficiency, solving a number of problems inherent with using steel springs that suspension designers have always dreamt they could eliminate.

- **Hydropneumatic is naturally a progressive spring-rate suspension;** i.e., the more it is compressed, the harder it becomes. This results in the suspension being extremely soft around its initial course (softer than a steel spring) but getting harder and harder as compressed (more than a steel spring). This is because of the properties of gas: halve its volume, and its pressure doubles. When the suspension operates, the ram is pushing oil into the sphere altering its gas volume (and therefore the pressure). This natural principle of hydropneumatics has not been met so far by any other type of suspension. The nearest is steel springs with a softer course and a harder course (two different spring rates, while hydropneumatics offer an infinite number of rates). Usually steel-sprung cars are either too soft ("comfortable"), or too stiff ("sporty"), or some intermediate compromise, while hydropneumatics offer "two cars in one".
- This advantage pays off in a spectacular way when *slaloming* (otherwise known as the 'moose test'): the swinging speeds and acceleration patterns of the body of a

hydropneumatic car offer ideal body control, and "load" the tyres in an ideal linear-like manner, helping to get the most out of them. A steel-sprung car acts more like a violently-swinging pendulum, "crashing" on its tyres (and abusing them) when leaning from side to side.

- The same natural law governing gases also ensures that **the suspension's spring-rate (hardness) is continuously adapted to the weight it has to carry**, and to infinite positions. For example, when the car is standing empty, the pressure within its spheres is in balance. If one passenger enters the car, this pressure becomes higher by the value of his weight (the gas in the spheres compressed to an equal degree, i.e. has now become "harder"). The car will have lost some height, so the self-leveling system immediately reacts and brings the car up to the predetermined ride height. The result is that the spring rate is kept constant, regardless of the load of the car. I.e., a car with 4 passengers and full payload will be equally well controlled as a car with just one passenger (bar the tyres, which of course remain at the same pressure.). With a steel-spring car, either the car would be set up to be comfortable with 1-2 passengers but getting too soft as more weight is added (becoming uncontrollable under full payload), or it would be too stiff with 1-2 passengers and okay on full payload.
- This effect is especially pronounced at the rear axle, where the designer of a steel-sprung car has to make the greatest compromise: the rear suspension has to be able to deal satisfactorily with a large range of load. Because of the above property of hydropneumatics, Citroën vehicles can have a rear that is set very soft; one can easily push the empty car down with his hand. When load is added, it stiffens as much as necessary. Steel-sprung cars need to have rear springs much stiffer than necessary for average daily driving.
- The self-levelling system makes it such that **there's always and at any time an equal travel available for suspension compression and extension**, no matter the car's load. Citroën have calculated that the ideal suspension should have at least about 18 cm of motion range, i.e. 9 cm each way, for achieving effective continuous contact between pavement and tyres (by absorbing any road unevenness). With a "height corrector" for each axle, the car suspension always remains at its ideal middle position, providing a steady compression and extension course, no matter the car's load. As you load a steel-sprung car, its bump absorption capability becomes totally asymmetrical (too small a compression margin and too much of an extension course available, and the suspension moves far from its ideal operating angles, reducing lateral/longitudinal grip, etc.).
- Very importantly, **the continuous self-levelling function also rids suspension design of a number of unwanted compromises** that commonly designers of steel-sprung cars have to incorporate: as the suspension is always functioning around one predetermined position, no matter the car's load, the various suspension-geometry issues become a much simpler equation to solve. A hydropneumatic suspension operates from its ideal angles at all times and conditions.
- The suspension being self-levelling, the possibility opens for dynamic height control. This has actually been implemented in Citroëns from the C5 I and onwards: the cars are programmed to lower by about 1 cm above a specified

speed, thus reducing aerodynamic resistance, improving fuel economy and increasing high-speed stability.

- Ride height is manually adjustable (in all hydropneumatic and Hydractive Citroëns) in 4 positions: "low", "drive", "mid-high", "highest". "Low" is only for service's purpose and should never be used in normal driving. "Mid-high" or "Highest" may be selected to tackle some road obstruction (flooding, pavements, off-road, etc) at very low speed .
- Because the suspension doesn't need to be set stiff to overcome all sorts of restrictions imposed by the steel spring, the ride comfort is excellent (the ride is described as floating above the road surface), with the difference that the suspension never 'wallows' uncontrollably like an equally soft car on springs would do. This preserves precise handling and road-holding (like a sports car). Orthopaedic doctors advise that patients with spinal injury or disk problems can only drive Citroëns with hydropneumatic suspension. The legendary Rolls-Royce comfort is partly due to this system equally fitted to millions of Citroëns sold to this day since 1955 with the DS. **The possibility of having such a soft suspension but NOT the uncontrolled wallowing (e.g., like many older American cars) is due to another natural property of nitrogen gas: it inherently has much less endogenous friction than steel.** In other words, it is relatively much more neutral, more inactive. Think of a leaf-spring being compressed: leave it free and it will pop and spend some time vibrating around its centre position till it comes to rest. This is due to its internal mechanical friction (due to the material), and this is why cars need shock absorbing dampers. A coil or torsion bar steel spring performs much better, (which is why it has long replaced leaf-springs in cars). Gas however behaves even better than the spring, in fact it represents a leap in effectiveness: compress a gas and release it: the gas will want to only return to its initial volume, not much more. Thus damping can be also reduced, resulting in an unearthly softness.
- This inertia of the gas is also the reason why on a hydropneumatic Citroën **the driver will many times not even realise the event of a blown tyre**—if not for the added noise—which can cause dynamic unrest and prove fatal on a steel-sprung car.
- The low-frequency wallowing characteristic of older Citroëns (prior to the BX) is due to the gas inertia as described above, and a soft damping. Commonly manufacturers believe that the optimal undulating frequency for a car's suspension is the one of human walking, i.e. about 0.2 cycles per second (0.2 Hz), thus many cars have this "rubbery", abrupt suspension feeling, which tends to increase as speed increases. Citroën tuned their cars to undulate at 1.6 Hz early on (DS, CX). Gradually they have brought this frequency down, with the Hydractive XM being set at 0.6 Hz (in the "soft" mode; in "hard", the car is sprung and damped like a sports car). The gas gives infinite possibilities: the operational frequency is just adjusted with the dampers (which look like disks the size of a large coin).
- The legendary comfort of Citroëns is also due to another factor, which is a specific choice in the set up of the system: **Citroën chose to hydraulically interconnect each wheel at the same axis.** Thus the two front wheels are connected with each other. And so are the rear wheels. This has a very specific

- result for body control: when one of the two wheels meets, say, a bump, that wheel will tend to compress and absorb the bump. In the degree not the entire height of the bump can be absorbed, the car's body will lift at that side. In the same time, through the anti roll bar, this wheel will exert force at the other side wheel and tend to also lift it in the same direction (compress the suspension). This is where the hydraulic interconnection of these two comes to play. In an ordinary steel-sprung car, this anti roll bar effect would mean that the car's body at the bump-absorbing side would lift, while it would tend to drop at the other side. This amplifies the bump's effect of destabilising the car and creating discomfort. In the Citroën system, the anti roll bar will also tend to do the same, but it is stopped by the hydraulic oil that is sent from the bump-side wheel at the moment it is pushed upwards to absorb the bump. Thus the suspension at the other side will receive a force opposing that of the anti roll bar, and of a degree of deflection equal to the size of the bump. This in effect translates into a much reduced overall feeling of impact from any bump, as the shock is effectively automatically shared with the wheel at the other side of each axis. In practice this feels as if the whole front or the whole rear is slightly lifting, rather than the car receiving an unpleasant shock from one side. Another solution, as e.g. implemented in the Austin Princess, (and pioneered with mechanical interconnection on the 1948 Citroen 2cv), is to interconnect the front and the rear wheel of each side. This has also beneficial results comfort-wise (the front and the rear share the impact forces) but also unwanted counter-effects on braking and accelerating: in braking the car tends to nose-dive (all hydraulic oil is pushed to the rear). In the Citroën set-up the adverse effect is that the car tends to roll a lot (the oil is pushed from one side to the other) however this is filtered by the anti roll bar (there's no equivalent item on the Princess to filter front-rear balance, though this issue was addressed on later versions of that suspension). This effect in Citroëns, perceived by many as the only potential disadvantage of the hydropneumatic suspension (although it has not real effects on the lateral accelerations the car can achieve), has been totally put under control with the advent of the Hydractive systems, from the XM onwards.
- The master cylinder ("brake doseur valve") on Citroëns includes specific solutions that take advantage of the hydropneumatic suspension, e.g. the pressure for rear braking is taken directly from the rear suspension (they are hydraulically connected). This makes that the braking force of the rear axle is continuously adjusted to the weight it carries (as pressure within rear suspension is equal to the weight it carries). So the rear brakes will come in significantly harder the more the rear is loaded.
 - It is a matter of minutes for the home mechanic to replace an old sphere—which includes the "spring" and "damper" in one—using a simple tool that can be home-made. Also, one is free to try various sphere combinations on his car, selecting from the several varieties available for the various Citroën models, thus going for a more "comfortable" or more "sporty" set up.
 - Compact suspension design, lies horizontally under the rear of the car avoiding suspension turrets taking up luggage space
 - Maintenance, for a do-it-yourselfer, is relatively easy, once you know what you are doing. It doesn't require any specific tools.

- Replacement of a suspension sphere is much easier and safer than replacing a conventional spring and shock-absorber arrangement.
- Inexpensive in mass production; for vehicles that would otherwise have a conventional power steering pump, hydropneumatic suspension adds no new equipment and in many cases results in a lower unsprung mass. Equally, the same system pressure produced from one central pump is used for braking (up to and including the Xantia).
- Upon body roll, the pressure exerted between the tires of the same axle is not subject to the same differential as on some other cars. The pressure in one suspension strut equals the pressure in the other through Pascal's law, potentially giving the 'light' tire more footprint pressure.
- Can be conveniently interconnected in the roll plane to improve roll stiffness and thus roll stability limit, especially for heavy vehicles.
- Can be connected in the pitch plane to improve braking dive and traction squat.
- If they are interconnected in the three-dimensional full car model, the interconnected hydro-pneumatic suspension could realize enhanced roll and pitch control during excitations arising from steering, braking/traction, road input and crosswind, as with the Hydractive arrangement
- Flexibility in the suspension strut design in the interconnected suspension system to realize desirable vertical, roll and pitch properties for different types of vehicles.
- Horizontal orientation of the rear suspension cylinders below the boot floor makes the full width of the boot is available for cargo.
- Mechanical steel spring suspension systems that try to replicate only some of the inherent advantages of hydropneumatic suspension (electronically adjustable shock absorbers) end up being lesser solutions and more complex to build and maintain than the straightforward hydropneumatic layout.
- People who are prepared to carry out simple maintenance can acquire a used luxury car for a fraction of the cost, as hydropneumatic suspension scares potential buyers and dealers despite more complex and maintenance-intensive systems on other cars. Most of the components are not repairable by a DIY mechanic, but they are easily exchanged for new or re-conditioned units. Pumps, height correctors, accumulators (including suspension "spheres"), steering units, etc. can all be reconditioned, and simply interchanged with the use of ordinary automotive mechanics' tools. Hydraulic fluid is drained and refilled with fresh, much like changing engine oil. Later Citroën automatic transmissions are conventional modern units similar to those of other makes.

Disadvantages

- Service sometimes requires a specifically trained mechanic, but can be done by any DIYer with knowledge of the system or the correct manual
- Hydropneumatic suspension systems can be expensive to repair or replace, **if** poorly maintained or contaminated with incompatible fluids.
- Failure of the hydraulic system will cause a drop in ride height and braking power will decrease. However, an acute failure will *not* lead to acute brake failure as the

accumulator sphere holds enough reserve pressure to ensure safe braking far beyond that needed to bring a vehicle with a failed system to a standstill.

Hydractive

Hydractive Suspension is a new automotive technology introduced by the French manufacturer Citroën in 1990. It describes a development of the 1954 Hydropneumatic suspension design using additional electronic sensors and driver control of suspension performance. The driver can make the suspension stiffen (sport mode) or ride in outstanding comfort (soft mode). Sensors in the steering, brakes, suspension, throttle pedal and gearbox feed information on the car's speed, acceleration, and road conditions to on-board computers. Where appropriate, and within milliseconds, these computers switched an extra pair of suspension spheres in or out of circuit, to allow the car a smooth supple ride in normal circumstances, or greater roll resistance for better handling in corners. This development keeps Citroën in the forefront of suspension design, given the widespread goal in the auto industry of an Active Suspension system. All auto suspension is a compromise between comfort and handling. Auto manufacturers try to balance these aims and locate new technologies that offer more of both.

Hydractive 1 and Hydractive 2

Citroën hydractive (Hydractive 1 and Hydractive 2) suspension was available on several models, including the XM and Xantia, which had a more advanced sub-model known as the Activa. Hydractive 1 suspension systems had two user presets, *Sport* and *Auto*. In the *Sport* setting the car's suspension was always kept in its firmest mode. In the *Auto* setting, the suspension was switched from soft to firm mode temporarily when a speed-dependent threshold in accelerator pedal movement, brake pressure, steering wheel angle, or body movement was detected by one of several sensors.

In Hydractive 2, the preset names were changed to *Sport* and *Comfort*. In this new version the *Sport* setting would no longer keep the suspension system in firm mode, but instead lowered the thresholds significantly for any of the sensor readings also used in *Comfort* mode, allowing for a similar level of body firmness during cornering and acceleration, without the sacrifice in ride quality the *Sport* mode in Hydractive 1 systems had caused.

Whenever the Hydractive 1 or 2 computers received abnormal sensor information, often caused by malfunctioning electrical contacts, the car's suspension system would be forced into its firm setting for the remainder of the ride.

Starting with Xantia model year 1994 and XM model year 1995, all models featured an additional sphere that functioned as a pressure reservoir, letting the car retain normal ride height for several weeks without running the engine.

Hydractive 3

The 2001 Citroën C5 has continued development of Hydractive suspension with Hydractive 3. Compared to earlier cars, the C5 stays at normal ride height even when the engine is turned off for an extended period, through the use of electronics. The C5 also uses a new, incompatible orange LDS fluid, rather than the familiar green LHM mineral oil used in millions of hydropneumatic vehicles.

A further improved Hydractive 3+ variation was for cars with top engines on the Citroën C5 and in 2005 was standard on the Citroën C6. Hydractive 3+ systems contain additional spheres that can be engaged and disengaged via a *Sport* button, resulting in a firmer ride.

The hydractive 3 hydraulic suspension has 2 automatic modes:

- Motorway position (lowering by 15 mm of the vehicle height above 110 km/h)
- Poor road surface position (raising by 13 mm of the vehicle height below 70 km/h)

The BHI of the hydractive 3 suspension calculates the optimum vehicle height, using the following information:

- Vehicle speed
- Front and rear vehicle heights

The 3+ hydractive hydraulic suspension has 3 automatic modes:

- Motorway position (lowering by 15 mm of the vehicle height above 110 km/h)
- Poor road surface position (raising by 13 mm of the vehicle height below 70 km/h)
- *Comfort* or *dynamic* suspension (variation of suspension firmness)

The BHI of the 3+ hydractive suspension calculates the optimum vehicle height, using the following information:

- Vehicle speed
- Front and rear vehicle heights
- Rotation speed of steering wheel
- Angle of rake of steering wheel
- Vehicle's longitudinal acceleration
- Vehicle's lateral acceleration
- Speed of suspension travel
- Movement of the accelerator throttle

C5 I (2001–2004)

- Hydractive hydraulic suspension 3: EW7J4 and DW10TD engines.
- Hydractive hydraulic suspension 3+: EW10J4, EW10D, ES9J4S and DW12TED4 engines.

C5 II (2004-2008)

- Hydractive hydraulic suspension 3: EW7J4, EW10A, DV6TED4 and DW10BTED4 engines.
- Hydractive hydraulic suspension 3+: ES9A and DW12TED4 engines (prior to RPO No 10645).

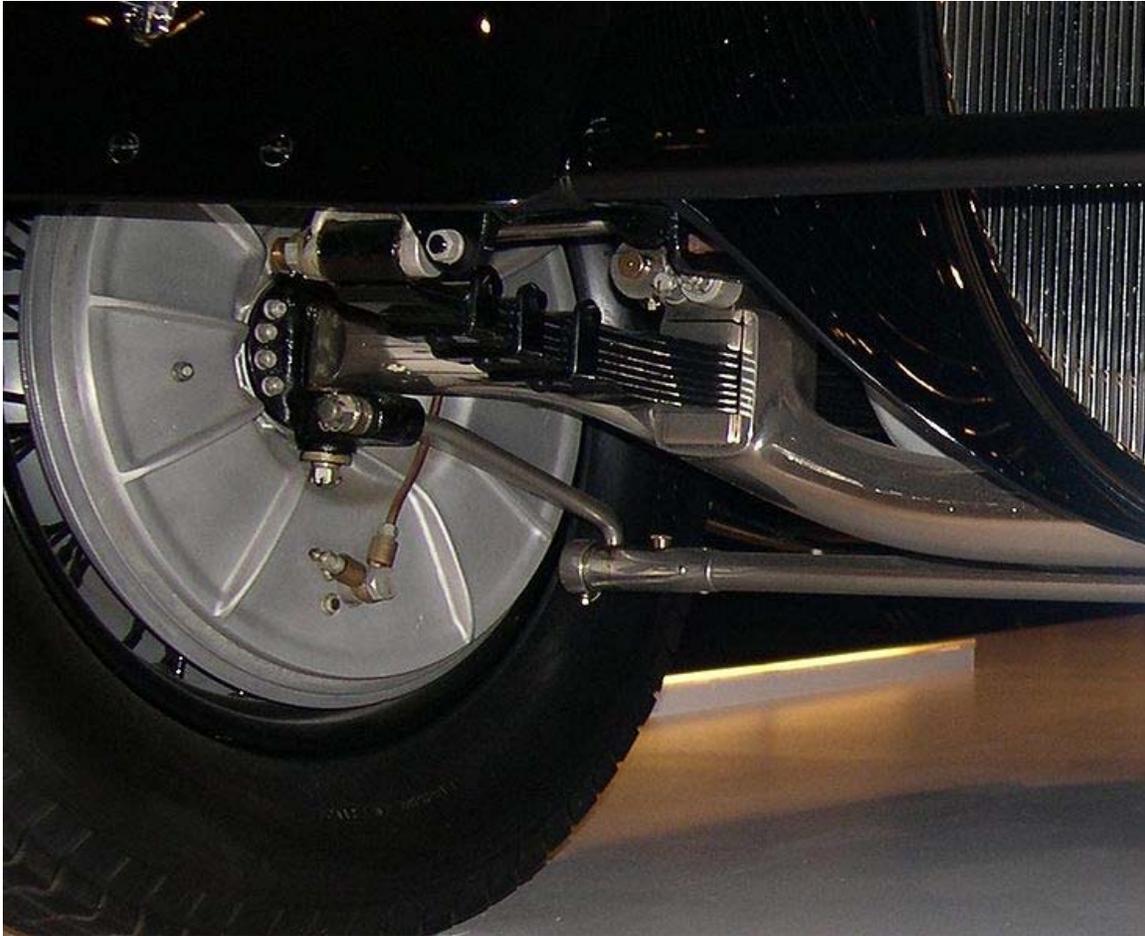
Chapter 7

Leaf Spring and Live Axle

Leaf spring



A traditional semi-elliptical Hotchkiss leaf spring arrangement. On the left, the spring is connected to the frame through a shackle.



Quarter-elliptical spring in a 1937 Bugatti Type 57SC

Originally called *laminated* or *carriage spring*, a **leaf spring** is a simple form of spring, commonly used for the suspension in wheeled vehicles. It is also one of the oldest forms of springing, dating back to medieval times.

An advantage of a leaf spring over a helical spring is that the end of the leaf spring may be guided along a definite path.

Sometimes referred to as a **semi-elliptical spring** or **cart spring**, it takes the form of a slender arc-shaped length of spring steel of rectangular cross-section. The center of the arc provides location for the axle, while tie holes are provided at either end for attaching to the vehicle body. For very heavy vehicles, a leaf spring can be made from several leaves stacked on top of each other in several layers, often with progressively shorter leaves. Leaf springs can serve locating and to some extent damping as well as springing functions. While the interleaf friction provides a damping action, it is not well controlled and results in stiction in the motion of the suspension. For this reason manufacturers have experimented with mono-leaf springs.

A leaf spring can either be attached directly to the frame at both ends or attached directly at one end, usually the front, with the other end attached through a shackle, a short swinging arm. The shackle takes up the tendency of the leaf spring to elongate when compressed and thus makes for softer springiness. Some springs terminated in a concave end, called a *spoon end* (seldom used now), to carry a swivelling member.

History

There were a variety of leaf springs, usually employing the word "elliptical". "Elliptical" or "full elliptical" leaf springs referred to two circular arcs linked at their tips. This was joined to the frame at the top center of the upper arc, the bottom center was joined to the "live" suspension components, such as a solid front axle. Additional suspension components, such as trailing arms, would be needed for this design, but not for "semi-elliptical" leaf springs as used in the Hotchkiss drive. That employed the lower arc, hence its name. "Quarter-elliptic" springs often had the thickest part of the stack of leaves stuck into the rear end of the side pieces of a short ladder frame, with the free end attached to the differential, as in the Austin Seven of the 1920s. As an example of non-elliptic leaf springs, the Ford Model T had multiple leaf springs over its differential that were curved in the shape of a yoke. As a substitute for dampers (shock absorbers), some manufacturers laid non-metallic sheets in between the metal leaves, such as wood.

Leaf springs were very common on automobiles, right up to the 1970s in Europe and Japan and late 70's in America when the move to front wheel drive, and more sophisticated suspension designs saw automobile manufacturers use coil springs instead. Today leaf springs are still used in heavy commercial vehicles such as vans and trucks, SUVs, and railway carriages. For heavy vehicles, they have the advantage of spreading the load more widely over the vehicle's chassis, whereas coil springs transfer it to a single point. Unlike coil springs, leaf springs also locate the rear axle, eliminating the need for trailing arms and a Panhard rod, thereby saving cost and weight in a simple live axle rear suspension.

A more modern implementation is the parabolic leaf spring. This design is characterised by fewer leaves whose thickness varies from centre to ends following a parabolic curve. In this design, inter-leaf friction is unwanted, and therefore there is only contact between the springs at the ends and at the centre where the axle is connected. Spacers prevent contact at other points. Aside from a weight saving, the main advantage of parabolic springs is their greater flexibility, which translates into vehicle ride quality that approaches that of coil springs. There is a trade-off in the form of reduced load carrying capability, however. The characteristic of parabolic springs is better riding comfort and not as "stiff" as conventional "multi-leaf springs". It is widely used on buses for better comfort. A further development by the British GKN company and by Chevrolet with the Corvette amongst others, is the move to composite plastic leaf springs.

Typically when used in automobile suspension the leaf both supports an axle and locates/partially locates the axle. This can lead to handling issues (such as 'axle tramp'), as the flexible nature of the spring makes precise control of the unsprung mass of the axle

difficult. Some suspension designs which use leaf springs do not use the leaf to locate the axle and do not have this drawback. The Fiat 128's rear suspension is an example.

Manufacturing process

Multi-leaf springs are made as follows:

1. Shearing of flat bar
2. Center punching
3. End Heating process forming (hot & cold process)
 1. Eye Forming / Wrapper Forming
 2. Diamond cutting / end trimming / width cutting / end tapering
 3. End punching / end grooving / end bending / end forging / eye grinding
4. Heat treatment
 1. Center hole punching / nibbing
 2. Camber forming
 3. Quenching
 4. Tempering
5. Surface preparation
 1. Shot peening / stress peening
 2. Painting
6. Eye bush preparation process
 1. Eye reaming / eye boring
 2. Bush insertion
 3. Bush reaming
7. Assemble
 1. Presetting & load testing
 2. Paint touch-up
 3. Marking & packing

Use by Blacksmiths

Because leaf springs are made of relatively high quality steel, they are a favorite material for blacksmiths. In countries such as Nepal, Bangladesh and Pakistan where traditional blacksmiths still produce a large amount of the country's tools, leaf springs from scrapped cars are frequently used to make knives, kukris, and other tools. They are also commonly used by amateur and hobbyist blacksmiths in Western countries.

Live axle



A live axle in a Jeep. This is the front suspension, using coil springs

A **live axle**, sometimes called a solid axle, is a type of beam axle suspension system that uses the driveshafts that transmit power to the wheels to connect the wheels laterally so that they move together as a unit.

A **live axle** consists of a central differential in a single housing that also contains the driveshafts that connect the differential to the driven wheels. The differential is connected to the engine via a swinging drive shaft and a universal joint. The complete assembly may typically be suspended with leaf springs, coil springs or air bags.

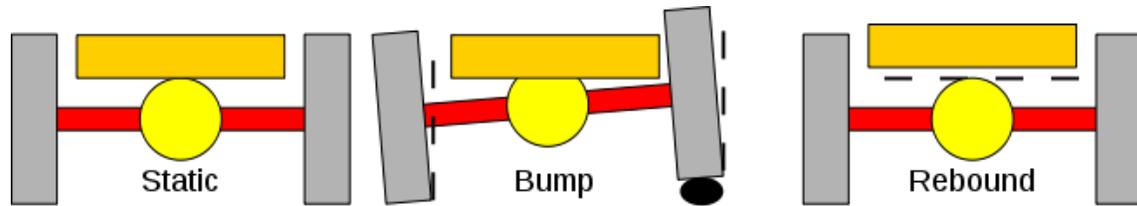
In small trucks solid front axles have generally been replaced by independent front suspension.

Some live axles use trailing arms, semi-trailing arms, Panhard rod, or Watt's linkage to control the vertical and lateral movements of the axle. Others, particularly older vehicles, use Hotchkiss drive, in which the leaf springs provide axle location as well as suspension.

Advantages and disadvantages

As with any beam axle, the advantages of the live axle are relative simplicity, lower manufacturing costs, lighter overall vehicle weight, and the fact that the axle and suspension systems take up little interior volume. Because the axle assembly is a fairly simple and rigid arrangement, it can easily be made strong and robust, which is an advantage for vehicles with substantial power or that are intended for use in rugged

environments or off-road usage. A further advantage of a live/beam axle in off-road use is that ground clearance under the axle remains constant, even if one wheel rises over a bump and the other doesn't.



Solid axle suspension characteristics: Camber change on bumps, none on rebound, large unsprung weight

The principal disadvantage is the negative effect on ride quality and handling. The wheels cannot move independently in response to bumps. Although the overall mass of the total suspension is low, the mass of the differential and driveshafts are part of the vehicle's unsprung weight, so the greater unsprung mass transmits larger forces to the body of the vehicle and its occupants. Conversely, in an independent rear suspension system the differential is rigidly attached to the vehicle. The lower unsprung mass of the suspension results in a greater ability to absorb imperfections in the road. In passenger car applications, often now fitted with multi-link independent suspension, the useful ability to change toe and camber independently left to right under cornering loads is not given with a live axle.

Applications

Until the 1980s the live axle was the most common rear suspension system on rear-wheel drive cars in the United States. It remains common on trucks, buses and other heavy vehicles, owing to its greater potential robustness and relatively low maintenance requirements, but most passenger cars have now adopted independent rear suspension instead.

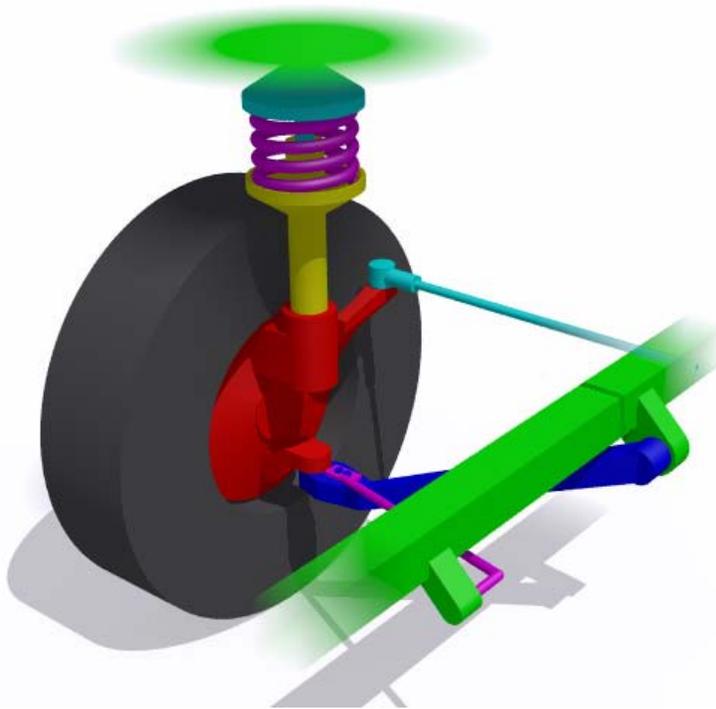
Examples of some passenger-vehicle types that have employed a live axle with various suspension elements are:

1. Leaf springs — the early Land-Rover, original Jeep, 1958-90 Toyota Land Cruiser (US-models), 1979-85 Toyota Hilux (US-models), 1985-95 Suzuki Samurai (US-models)
2. Coil springs — the Range Rover 1 & 2, Rover SD1, Volvo 240, current (1997-) Jeep Wrangler models; ;
3. Panhard rods - the Ford Mustang; Chevrolet Camaro

Chapter 8

MacPherson Strut and Multi-Link Suspension

MacPherson strut



A simple MacPherson strut suspension on the left front wheel of a rear-wheel drive vehicle

Red section: Steering knuckle or hub carrier
Blue section: Lower control arm or track control arm

Light blue section: Steering gear tie rod

Lower purple section: Radius rod

Upper purple Section: Coil spring

Yellow section: Tubular housing containing shock absorber or damper

The **MacPherson strut** is a type of car suspension system which uses the axis of a telescopic damper as the upper steering pivot. It is widely used in modern vehicles and named after Earle S. MacPherson, who developed the design.

History

Earle S. MacPherson developed the design of the strut in 1949 partially based on designs created by Guido Fornaca of FIAT in the mid-1920s. It is possible the MacPherson was inspired by the suspension on the French Cottin-Desgouttes that used the same design, but with leaf springs. Cottin-Desgouttes front suspension was in turn inspired by J. Walter Christie's 1904 design and he was inspired by plants.

The first car to feature MacPherson struts was the 1949 Ford Vedette, and it was also adopted in the 1951 Ford Consul and later Zephyr. MacPherson originally created the design for use at all four wheels (Mitsubishi Starion, for example), but production applications used it only for the front suspension, where it provides a steering pivot (kingpin) as well as a suspension mounting for the wheel. In 1957 Colin Chapman of Lotus applied the design to the rear suspension of the Lotus Elite. As a result, strut suspension at the rear of an automobile are now commonly called Chapman struts.

Design

MacPherson struts consist of a wishbone or a substantial compression link stabilized by a secondary link which provides a bottom mounting point for the hub or axle of the wheel. This lower arm system provides both lateral and longitudinal location of the wheel. The upper part of the hub is rigidly fixed to the inner part of the strut proper, the outer part of which extends upwards directly to a mounting in the body shell of the vehicle.

To be really successful, the MacPherson strut required the introduction of unibody (or monocoque) construction, because it needs a substantial vertical space and a strong top mount, which unibodies can provide, while benefiting them by distributing stresses. The strut will usually carry both the coil spring on which the body is suspended and the shock absorber, which is usually in the form of a cartridge mounted within the strut. The strut also usually has a steering arm built into the lower inner portion. The whole assembly is very simple and can be preassembled into a unit; also by eliminating the upper control arm, it allows for more width in the engine bay, which is useful for smaller cars, particularly with transverse-mounted engines such as most front wheel drive vehicles have. It can be further simplified, if needed, by substituting an anti-roll bar (torsion bar) for the radius arm. For those reasons, it has become almost ubiquitous with low cost manufacturers. Furthermore, it offers an easy method to set suspension geometry.

Advantages and Disadvantages

Although it is a popular choice due to its simplicity and low manufacturing cost, the design has a few disadvantages, with regards to the quality of ride it provides and how it affects the handling of the car. Geometric analysis shows it cannot allow vertical movement of the wheel without some degree of either camber angle change, sideways movement, or both. It is not generally considered to give as good handling as a double wishbone suspension, because it allows the engineers less freedom to choose camber change and roll center. Another drawback is that it tends to transmit noise and vibration from the road directly into the body shell, giving higher noise levels and a "harsh" feeling to the ride compared with double wishbones, requiring manufacturers to add extra noise reduction or cancellation and isolation mechanisms. Also, because of its greater size and robustness and greater degree of attachment to the vehicle structure, when the internal seals of the shock absorber portion wear out replacement is expensive compared to replacing a simple shock absorber.

Despite these drawbacks, the MacPherson strut setup is still used on high performance cars such as the Porsche 911, all current BMWs (including the new Mini) except the 2007 X5, 2009 7-series, 2010 5-series and 5-series GT, the Alfa Romeo Mito and 2010 Giulietta, and several Mercedes-Benz models.

The Porsche 911 up until the 1989 model year (964) use Macpherson strut designs that do not have coil springs, using a torsion bar suspension instead.

Multi-link suspension

Multi-link rear suspension of the 5-link type

A **multi-link suspension** is a type of vehicle suspension design typically used in independent suspensions, using three or more lateral arms, and one or more longitudinal arms. A wider definition considers any independent suspensions having 3 control arms or more multi-link suspensions. These arms do not have to be of equal length, and may be angled away from their 'obvious' direction.

Typically each arm has a spherical joint (ball joint) or rubber bushing at each end. Consequently they react to loads along their own length, in tension and compression, but not in bending. Some multi-links do use a trailing arm or wishbone, which has two bushings at one end.

On a front suspension one of the lateral arms is replaced by the tie-rod, which connects the rack or steering box to the wheel hub.

In order to simplify understanding it is usual to consider the function of the arms in each of three orthogonal planes.

Plan view

The arms have to control toe/steer and lateral compliance. This needs a pair of arms longitudinally separated.

Front view

The arms have to control camber, particularly the way that the camber changes as the wheel moves up (into jounce, or bump) and down into rebound or droop.

Side view

The arms have to react traction and braking loads, usually accomplished via a longitudinal link. They also have to control caster. Note that brake torques also have to be reacted - either by a second longitudinal link, or by rotating the hub, which forces the lateral arms out of plane, so allowing them to react 'spin' forces, or by rigidly fixing the longitudinal link to the hub.

Advantages of multi-link suspension

Multi-link suspension allows the auto designer the ability to incorporate both good ride quality and good car handling in the same vehicle.

In its simplest form the multi-link suspension is orthogonal - that is, it is possible to alter one parameter in the suspension at a time, without affecting anything else. This is in direct contrast to a double wishbone suspension where moving a hardpoint or changing a bushing compliance will affect two or more parameters.

Advantages also extend to off road driving. A multi-link suspension will allow the vehicle to flex more; this means simply that the suspension will be able to move more easily to conform to the varying angles of off roading. Multi-link equipped vehicles are ideally suited for sports such as rock crawling and desert racing. A side note to the use of multi-link suspension in desert racing: the use of a good sway bar is needed to counter body roll.

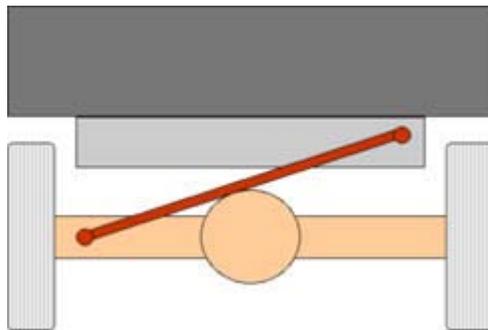
Disadvantages of multi-link suspension

Multilink suspension is costly and complex. It is also difficult to tune the geometry without a full 3D computer aided design analysis. Compliance under load can have an important effect and must be checked using a multibody simulation software.

Chapter 9

Panhard Rod and Swing Axle

Panhard rod



A **Panhard rod** (also called **Panhard bar** or **track bar**) is a component of a car suspension system that provides lateral location of the axle. Originally invented by the Panhard automobile company of France in the early twentieth century, this device has been widely used ever since.

While the purpose of the suspension of an automobile is to allow the wheels to move vertically with respect to the body, it is undesirable to allow them to move forward and backwards (longitudinally), or side to side (laterally). The Panhard rod is designed to prevent lateral movement. It is a simple device, consisting of a rigid bar running sideways in the same plane as the axle, connecting one end of the axle to the car body or chassis on the opposite side of the vehicle. The bar is attached on either end with pivots that permit it to swivel upwards and downwards only, so that the axle is allowed to move in the vertical plane only. This does not effectively locate the axle longitudinally, therefore it is usually used in conjunction with trailing arms which stabilize the axle in the longitudinal direction. This arrangement is not usually used with a leaf spring suspension, where the springs themselves supply enough lateral rigidity, but only with coil spring suspensions.



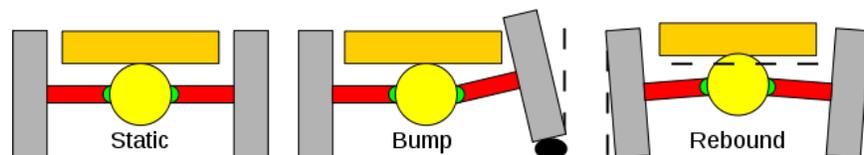
Solid axle and Panhard rod on a 2002 Mazda MPV

The advantage of the Panhard rod is its simplicity. Its major disadvantage is that the axle must necessarily move in an arc relative to the body, with the radius equal to the length of the Panhard rod. If the rod is too short, there will be excessive sideways movement between the axle and the body at the ends of the spring travel. Therefore, the Panhard rod is less desirable on smaller cars than larger ones. A suspension design that is similar but dramatically reduces the sideways component of the axle's vertical travel is Watt's linkage.

Some vehicles including Land Rovers with live axle suspensions use a **Panhard rod** as a component of the front suspension where Watt's linkage is not an option.

Swing axle

A **swing axle** is a simple type of independent suspension first used in early aircraft (1910 or before), such as the Sopwith and Fokker, usually with rubber bungee and no damping.



Swing axle suspension characteristics: Camber change on bumps, "jacking" on rebound

Some later motor-car rear swing axles have universal joints connecting the driveshafts to the differential, which is attached to the chassis. They do not have universal joints at the wheels: the wheels are always perpendicular to the driveshafts. Swing axle suspensions traditionally used leaf springs and shock absorbers. Volkswagens built before 1967 used torsion bars as their spring.

Comparison

This type of suspension was considered better than the more typical live axle for two reasons:

1. It reduced unsprung weight since the differential is mounted to the chassis
2. It eliminates sympathetic camber changes on opposite wheels

Shortcomings

However, there are a number of shortcomings to this arrangement:

1. A great amount of single-wheel camber change is experienced, since the wheel is always perpendicular to the driveshaft
2. "Jacking" on suspension unloading (or rebound) causes positive camber changes on both sides, which (In extreme cases) can overturn the car.
3. Reduction in cornering forces due to change in camber can lead to oversteer — a dynamically unstable condition where a vehicle can lose control and spin — and in extreme cases lift-off oversteer.

Solutions

These problems were evident on Volkswagens up until 1967, the Mercedes-Benz 190SL and 300SL, the early versions of the Porsche 356, the Triumph Herald, Vitesse and Spitfire, Tatra T603, Renault Dauphine, Volkswagen Beetle and others.



1964 Corvair swing-axle rear suspension with transverse leaf spring

Mercedes-Benz addressed the handling issues by producing swing axles with a single-pivot point located under the differential, and thus well below the axle. This configuration markedly reduced the tendency to "jack-up" and the later low pivot swing-axle equipped cars were praised in contemporary publications for their handling. The low-pivot swing-axle remained in production with Mercedes-Benz W108 280SE and 300SEL until 1972. It was fitted to the 300SEL 6.3, which was during the early 70s the worlds fastest production sedan. AMG-modified 6.3s were also raced with the stock swing axle.

The Renault Dauphine, Volkswagen Beetle and first generation Chevrolet Corvair (1960–1964) used a *tire pressure differential* strategy to eliminate oversteer characteristics of their swing axle suspensions — specifically low front and high rear tire pressure —

which induced understeer. Nonetheless, the *tire pressure differential* strategy offered a significant disadvantage: owners and mechanics could inadvertently but easily re-introduce oversteer characteristics by over-inflating the front tires (e.g., to typical pressures for other cars with other suspension systems).

Safety

Ralph Nader in his 1965 book *Unsafe at Any Speed* highlighted accidents related to 1960-1963 models of the first generation Chevrolet Corvair swing-axle design and identified a Chevrolet engineer that had fought management who eliminated a front anti-roll bar for cost reasons. 1964 models were fitted with a front roll bar as standard equipment, in addition to a rear transverse leaf spring thus improving emergency maneuver stability. Second generation Corvairs (1965–1969) used a true independent rear suspension (IRS) system.

The Hillman Imp designers learned from the problems with the Corvair, having crashed one at a relatively low speed, and designed their rear-engined car with semi-trailing arm suspension at the rear. However, to attain correct handling balance, they actually used swing axle geometry at the front, with the steering pivots mounted at the outer ends of single swing wishbones. However, these caused too much understeer and uneven tyre wear, and modifications were made to reduce the positive camber of the front wheels by lowering the swing axle pivot points. Aftermarket kits were also available to do this, and an inexpensive alternative was to insert a tapered shim to change the inclination of the kingpin carrier relative to the wishbone.

Replacement

Swing axles were supplanted by De Dion tube axels in the late 1960s, though live axles remained the most common. Most rear suspensions have been replaced by more modern independent suspensions in recent years, and both swing and deDion types are virtually unused today. One exception is the Czech truck manufacturer Tatra, which uses swing axles and a central 'backbone' tube instead of more common solid axles. This system is claimed to give greater rigidity and better performance on poor quality roads and off road.

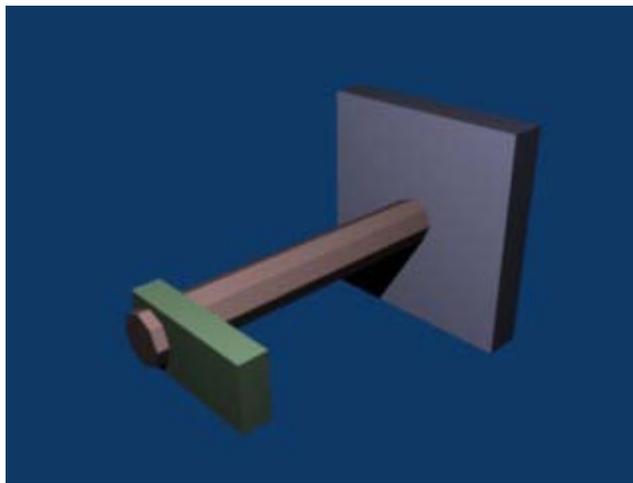
Variations

Another use of the swing axle concept is Ford's "Twin I-Beam" front suspension for trucks. This has solid axles (so they do not transmit power). Though it is touted as an independent suspension system in that each tire rises and falls without affecting the position of the other, the parallelogram action of the A-arm suspension system is not present. Each tire in fact moves with a similar camber change to that of the powered swing axles for the rear wheels listed above. But the pivot point of the axles is located not in the middle of the car but nearly on the other beam of the chassis, so the effect is far less hazardous.

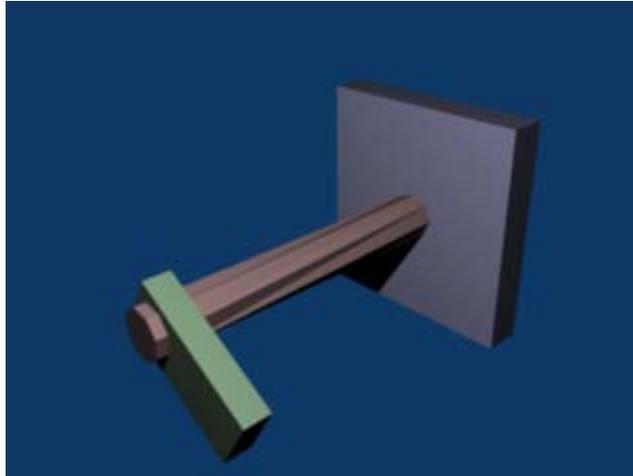
Chapter 10

Torsion Bar Suspension and Trailing Arm

Torsion bar suspension



A torsion bar with no load applied.



A torsion bar with a load applied.



A front VW Beetle suspension cross-section

A **torsion bar suspension**, also known as a torsion spring suspension and incorrectly as a **torsion beam**, is a general term for any vehicle suspension that uses a torsion bar as its main weight bearing spring. One end of a long metal bar is attached firmly to the vehicle chassis; the opposite end terminates in a lever, mounted perpendicular to the bar, that is attached to a suspension arm, spindle or the axle. Vertical motion of the wheel causes the bar to twist around its axis and is resisted by the bar's torsion resistance. The effective spring rate of the bar is determined by its length, cross section, shape and material.

Usage

Torsion bar suspensions are currently used on armoured fighting vehicles or tanks like the T-72 (Many tanks later in World War II used this suspension), trucks and SUVs from Ford, Dodge, GM, Mitsubishi, Mazda, Nissan and Toyota. Manufacturers change the torsion bar or key to adjust the ride height, usually to compensate for heavier or lighter engine packages. While the ride height may be adjusted by turning the adjuster bolts on the stock torsion key, rotating the stock keys too far can bend the adjusting bolt and (more importantly) place the shock piston outside the standard travel. Over-rotating the torsion bars can also cause the suspension to hit the bump stop prematurely, causing a harsh ride. Aftermarket forged torsion key kits use relocked adjuster keys to prevent over-rotation, as well as shock brackets that keep the piston travel in the stock position.

Advantages and disadvantages

The main advantages of torsion bar suspension are durability, easy adjustability of ride height, and small profile along the width of the vehicle. It takes up less of the vehicle's interior volume compared to coil springs. A disadvantage is that torsion bars, unlike coil springs, usually cannot provide a progressive spring rate. In most torsion bar systems, ride height (and therefore many handling features) may be changed by simply adjusting bolts that connect the torsion bars to the steering knuckles. In most cars with this type of suspension, swapping torsion bars for a different spring rate is usually an easy task.

Leveling

Some vehicles use torsion bars to provide automatic levelling, using a motor to tighten the bars to provide greater resistance to load and, in some cases (depending on the speed with which the motors can act), to respond to changes in road conditions. Height adjustable suspension has been used to implement a wheel-change mode where the vehicle is raised on three wheels and the remaining wheel is lifted off the ground without the aid of a jack.

History

Before World War II, the front wheel drive Citroen Traction Avant (1934) had independent front torsion bar suspension and a flexible trailing dead axle, also sprung by torsion bars. The flexibility of the axle beam providing wheel location features like a twist beam axle. The Czechoslovakian Tatra cars designed by Professor Hans Ledwinka in the mid-1930s used all round independent torsion bar suspension, along with air cooled rear engines. Also in the 1930s, prototypes of the first Volkswagen Beetle incorporated torsion bars—especially its transverse mounting style. Ledwinka's concept had been copied by Ferdinand Porsche, whose successors later had to acknowledge the influence of Ledwinka's sophisticated Tatra models on the Porsche-designed Kdf-Wagen of 1938 (later renamed the VW Beetle), a post-war lawsuit resulting in a DM3,000,000 settlement paid by Volkswagen to Ringhoffer-Tatra in 1961.

The system was applied to many new armored fighting vehicle designs during the Second World War. It was used extensively in European cars Renault, Citroën and Volkswagen, as well as by Packard in the 1950s. The Packard used torsion bars at both front and rear, and interconnected the front and rear systems to improve ride quality. The then revolutionary Jaguar E-Type introduced in 1961 had a unique torsion bar front suspension and a independent coil spring rear suspension using four shock absorbers with concentric springs.

The most famous American passenger car application was the Chrysler system used beginning with the 1957 model year, although Chrysler's "Torsion-Aire" suspension was only for the front; the same basic system (longitudinal mounting) was maintained until the 1981 introduction of the K-car. A reengineered torsion bar suspension, introduced with the 1976 Dodge Aspen, introduced transverse-mounted torsion bars (possibly based on the Volkswagen Type 3 passenger car) until production ended in 1989 (with Chrysler's M platform). Light duty Dodge trucks however continue to use torsion bars on their front suspension.

General Motors has used torsion bars since 1966, starting with the E-platform vehicles (Oldsmobile Toronado, Cadillac Eldorado), 4 wheel drive S-10 pickups & Astro vans, and since 1988, full size trucks (GMT400, GMT800, and GMT900 series).

Porsche used torsion bar suspension for their 911 series from 1963 until 1989 with the introduction of the 964.

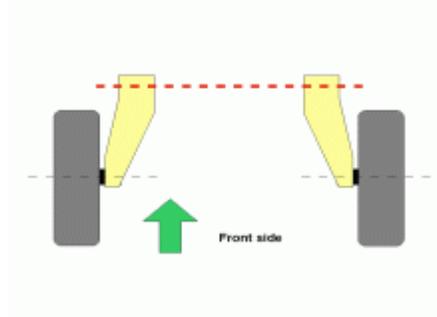
Variations

Some front-wheel drive automobiles use a related type of torsion beam suspension, usually called a twist beam rear suspension, in which the rear wheels are carried on trailing arms connected by a laterally mounted torsion beam. The torsion beam functions both as wheel locating arm and as an anti-roll bar to resist lateral motion of the wheels as the body leans in turns. Its advantages are that it is inexpensive to manufacture and install, and engages a minimum amount of interior volume, leaving more space for the carriage of passengers, cargo, and other components. Because the torsion beam acts in the lateral plane, not vertically, the twist beam axle cannot provide ride height adjustment, and it suffers, to some extent, similar car handling limitations as other beam axle suspensions. However these limitations may not be apparent on the road, because of the trend towards firmer, more sporty suspension setups with more limited wheel travel. Twist-beam rear suspensions were pioneered on the Volkswagen Golf in the early 1970s, and remain common on compact cars and minivans.

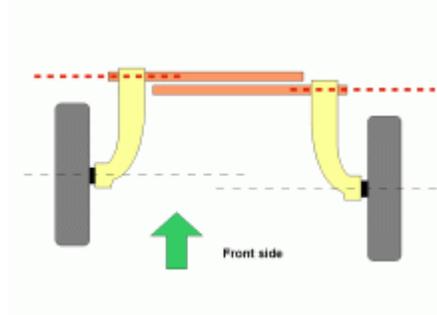
Other uses

Torsion bars were sometimes used instead of conventional coil valve springs in some older motorcycles, such as the Honda CB450.

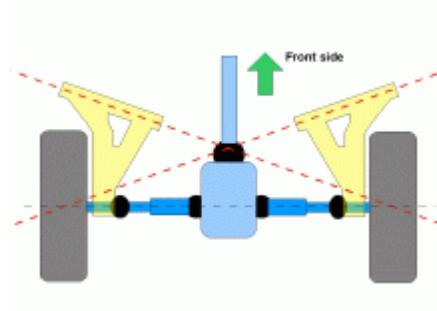
Trailing arm



Trailing arm rear suspension of FF cars



Rear suspension of Renault 4 and Renault 5



Semi-trailing arm suspension

A **trailing-arm suspension** is an automobile suspension design in which one or more arms (or "links") are connected between (and perpendicular to and forward of) the axle and the chassis. It is usually used on rear axles. A "leading arm", as used on a Citroën 2CV, has an arm connected between (and perpendicular to, and to the rear of) the axle and the chassis. It is used on the front axle.



Semi-trailing arm suspension of a 1969 Volkswagen Beetle

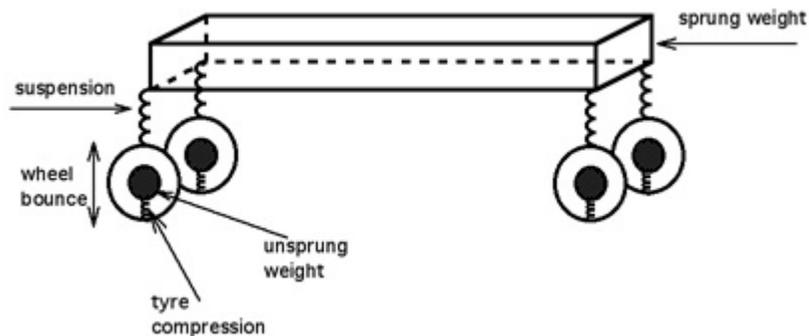
Trailing-arm designs in live axle setups often use just two or three links and a Panhard rod to locate the wheel laterally. A trailing arm design can also be used in an independent suspension arrangement. Each wheel hub is located only by a large, roughly triangular arm that pivots at one point, ahead of the wheel. Seen from the side, this arm is roughly parallel to the ground, with the angle changing based on road irregularities. A twist-beam rear suspension is very similar except that the arms are connected by a beam, used to locate the wheels and which twists and has an anti-roll effect.

A **semi-trailing arm suspension** is a simple independent rear suspension system for automobiles where each wheel hub is located only by a large, roughly triangular arm that pivots at two points. Viewed from the top, the line formed by the two pivots is somewhere between parallel and perpendicular to the car's longitudinal axis; it is generally parallel to the ground. Trailing-arm and multilink suspension designs are much more commonly used for the rear wheels of a vehicle where they can allow for a flatter floor and more cargo room. Many small, front-wheel drive vehicles feature a MacPherson strut front suspension and trailing-arm rear axle

Chapter 11

Unsprung Mass and Wheel Alignment

Unsprung mass



In a ground vehicle with a suspension, the **unsprung weight** (or the **unsprung mass**) is the mass of the suspension, wheels or tracks (as applicable), and other components directly connected to them, rather than supported by the suspension. (The mass of the body and other components supported by the suspension is the sprung mass.) Unsprung weight includes the mass of components such as the wheel axles, wheel bearings, wheel hubs, tires, and a portion of the weight of driveshafts, springs, shock absorbers, and suspension links. Even if the vehicle's brakes are mounted outboard (i.e., within the wheel), their weight is still considered part of the unsprung weight.

Effects of Unsprung Weight

The unsprung weight of a wheel controls a trade-off between a wheel's bump-following ability and its vibration isolation. Bumps and surface imperfections in the road cause tyre compression—which induces a force on the unsprung weight. The unsprung weight then responds to this force with movement of its own. The amount of movement, for short

bumps, is inversely proportional to the weight - a lighter wheel which readily moves in response to road bumps will have more grip and more constant grip when tracking over an imperfect road. For this reason, lighter wheels are sought especially for high-performance applications. In contrast, a heavier wheel which moves less will not absorb as much vibration; the irregularities of the road surface will transfer to the cabin through the geometry of the suspension and hence ride quality and road noise are deteriorated. For longer bumps that the wheels follow, greater unsprung mass causes more energy to be absorbed by the wheels and makes the ride worse.

Pneumatic or elastic tires help by providing some springing for most of the (otherwise) unsprung mass, but the damping that can be included in the tires is limited by considerations of fuel economy and overheating. The shock absorbers, if any, damp the spring motion also and must be less stiff than would optimally damp the wheel bounce. So the wheels execute some vibrations after each bump before coming to rest. On dirt roads and perhaps on some softly paved roads, these motions form small bumps, known as corrugations, washboarding or "corduroy" because they resemble smaller versions of the bumps in roads made of logs. These cause sustained wheel bounce in subsequent vehicles, enlarging the bumps.

High unsprung weight also exacerbates wheel control issues under hard acceleration or braking. If the vehicle does not have adequate wheel location in the vertical plane (such as a rear-wheel drive car with Hotchkiss drive, a live axle supported by simple leaf springs), vertical forces exerted by acceleration or hard braking combined with high unsprung mass can lead to severe wheel hop, compromising traction and steering control.

As mentioned above, there is a positive effect of unsprung mass. High frequency road irregularities, such as the gravel in an asphalt or concrete road surface, are isolated from the body more completely because the tires and springs act as separate filter stages, with the unsprung weight tending to uncouple them. Likewise, sound and vibration isolation is improved (at the expense of handling), in production automobiles, by the use of rubber bushings between the frame and suspension, by any flexibility in the frame or body work, and by the flexibility of the seats.

Unsprung Weight and Vehicle Design

Unsprung weight is largely a function of the design of a vehicle's suspension and the materials used in the construction of suspension components. Beam axle suspensions, in which wheels on opposite sides are connected as a rigid unit, generally have greater unsprung weight than independent suspension systems, in which the wheels are suspended and allowed to move separately. Heavy components such as the differential can be made part of the sprung weight by connecting them directly to the body (as in a de Dion tube rear suspension). Lightweight materials, such as aluminum, plastic, carbon fiber, and/or hollow components can provide further weight reductions at the expense of greater cost and/or fragility.

Inboard brakes can significantly reduce unsprung weight, but put more load on half axles and (constant velocity) universal joints, and require space that may not be easily accommodated. If located next to a differential or transaxle, waste heat from the brakes may overheat the differential or vice versa, particularly in hard use, such as motor racing. They also make anti-dive suspension characteristics harder to achieve as the moment created by the act of braking is not reacted on the suspension arms.

Scooter-type motorcycles use an integrated engine-gearbox-final drive system that pivots as part of the rear suspension and hence is partly unsprung. This arrangement is linked to the use of quite small wheels, further impacting the reputation for road-holding.

Wheel alignment

Wheel alignment sometimes referred to as **tracking**, is part of standard automobile maintenance that consists of adjusting the angles of the wheels so that they are set to the car maker's specification. The purpose of these adjustments is to reduce tire wear, and to ensure that vehicle travel is straight and true (without "pulling" to one side). Alignment angles can also be altered beyond the maker's specifications to obtain a specific handling characteristic. Motorsport and off-road applications may call for angles to be adjusted well beyond "normal" for a variety of reasons.

Primary angles

The primary angles are the basic angle alignment of the wheels relative to each other and to the car body. These adjustments are the camber, caster and toe. On some cars, not all of these can be adjusted on every wheel.

These three parameters can be further categorized into front and rear, so summarily the parameters are:

- Front: Caster (right & left)
- Front: Camber (right & left)
- Front: Toe (left, right & total)
- Rear: Camber (left & right)
- Rear: Toe (left, right & total)
- Rear: Thrust angle

Secondary angles

The secondary angles include numerous other adjustments, such as:

- SAI (left & right)
- Included angle (left & right)
- Toe out on turns (left & right)
- Maximum Turns (left & right)

- Toe curve change (left & right)
- Track width difference
- Wheel base difference
- Front ride height (left & right)
- Rear ride height (left & right)
- Frame angle

Setback (front & rear) is often referred as a wheel alignment angle. However setback simply exists because of the measuring system and does not have any specification from car manufacturers.

Measurement

A camera unit (sometimes called a "head") is attached to a specially designed clamp which holds on to a wheel. There are usually four camera units in a wheel alignment system (a camera unit for each wheel). The camera units communicate their physical positioning with respect to other camera units to a central computer which calculates and displays how much the camber, toe and caster are misaligned.

Often with alignment equipment, these "heads" can be a large precision reflector. In this case, the alignment "tower" contains the cameras as well as arrays of LEDs. This system flashes one array of LEDs for each reflector whilst a camera centrally located in the LED array "looks for" an image of the reflectors patterned face. These cameras perform the same function as the other style of alignment equipment, yet alleviate numerous issues prone to relocating a heavy precision camera assembly on each vehicle serviced.

Chapter 12

Automobile Handling

Automobile handling and **vehicle handling** are descriptions of the way wheeled vehicles perform transverse to their direction of motion, particularly during cornering and swerving. It also includes their stability when moving at rest. Handling and braking are the major components of a vehicle's "active" safety. The maximum lateral acceleration is sometimes discussed separately as "road holding". (This discussion is directed at road vehicles with at least three wheels, but some of it may apply to other ground vehicles.) Automobiles driven on public roads whose engineering requirements emphasize handling over comfort and passenger space are named sports cars.

Factors that affect a car's handling

Weight distribution

Center of mass height

The center of mass height, relative to the track, determines load transfer, (related to, but not exactly weight transfer), from side to side and causes body lean. When tires of a vehicle provide a centripetal force to pull it around a turn, the momentum of the vehicle actuates load transfer in a direction going from the vehicle's current position to a point on a path tangent to the vehicle's path. This load transfer presents itself in the form of body lean.

Height of the center of mass relative to the wheelbase determines load transfer between front and rear. The car's momentum acts at its center of mass to tilt the car forward or backward, respectively during braking and acceleration. Since it is only the downward force that changes and not the location of the center of mass, the effect on over/under steer is *opposite* to that of an actual change in the center of mass. When a car is braking, the downward load on the front tires increases and that on the rear decreases, with corresponding change in their ability to take sideways load.

A lower center of mass a principal performance advantage of sports cars, compared to sedans and (especially) SUVs. Some cars have body panels made of lightweight materials partly for this reason.

Body lean can also be controlled by the springs, anti-roll bars or the roll center heights.

Center of mass

The ideal weight distribution is "50/50" (i.e. the center of mass is mid-way between the front and rear axles). In steady-state cornering, front-heavy cars tend to understeer and rear-heavy cars to oversteer, all other things being equal. The mid-engine design seeks to achieve the ideal center of mass, though front-engine design has the advantage of permitting a more practical engine-passenger-baggage layout, and when engineered correctly can have as neutral (close to or at 50:50) weight distribution as a mid engine car. All other parameters being equal, at the hands of an expert professional driver a neutrally balanced mid-engine car can corner faster, but a FR layout car is easier to drive at the limit. Some good examples of these layouts are Ferrari F360 and Toyota MR2 for mid-engine design, and BMW M3 and Mazda MX-5 for the second.

The rearward weight bias preferred by sports and racing cars results from handling effects during the transition from straight-ahead to cornering. During corner entry the front tires, in addition to generating part of the lateral force required to accelerate the car's center of mass into the turn, also generate a torque about the car's vertical axis that starts the car rotating into the turn. However, the lateral force being generated by the rear tires is acting in the opposite torsional sense, trying to rotate the car out of the turn. For this reason, a car with "50/50" weight distribution will understeer on initial corner entry. To avoid this problem, sports and racing cars often have a more rearward weight distribution. In the case of pure racing cars, this is typically between "40/60" and "35/65". This gives the front tires an advantage in overcoming the car's moment of inertia (yaw angular inertia), thus reducing corner-entry understeer.

Using wheels and tires of different sizes (proportional to the weight carried by each end) is a lever automakers can use to fine tune the resulting over/understeer characteristics.

Roll angular inertia

This increases the time it takes to settle down and follow the steering. It depends on the (square of the) height and width, and (for a uniform mass distribution) can be approximately calculated by the equation: $I = M(\text{height}^2 + \text{width}^2) / 12$.

Greater width, then, though it counteracts center of gravity height, hurts handling by increasing angular inertia. Some high performance cars have light materials in their fenders and roofs partly for this reason.

Yaw and pitch angular inertia (polar moment)

Unless the vehicle is very short, compared to its height or width, these are about equal. Angular inertia determines the rotational inertia of an object for a given rate of rotation. The yaw angular inertia tends to keep the direction the car is pointing changing at a constant rate. This makes it slower to swerve or go into a tight curve, and it also makes it slower to turn straight again. The pitch angular inertia detracts from the ability of the suspension to keep front and back tire loadings constant on uneven surfaces and therefore contributes to bump steer. Angular inertia is an integral over the *square* of the distance from the center of gravity, so it favors small cars even though the lever arms (wheelbase and track) also increase with scale. (Since cars have reasonable symmetrical shapes, the off-diagonal terms of the angular inertia tensor can usually be ignored.) Mass near the ends of a car can be avoided, without re-designing it to be shorter, by the use of light materials for bumpers and fenders or by deleting them entirely.

Suspension

Automobile suspensions have many variable characteristics, which are generally different in the front and rear and all of which affect handling. Some of these are: spring rate, damping, straight ahead camber angle, camber change with wheel travel, roll center height and the flexibility and vibration modes of the suspension elements. Suspension also affects unsprung weight.

Many cars have suspension that connects the wheels on the two sides, either by a sway bar and/or by a solid axle. The Citroën 2CV has interaction between the front and rear suspension.

The flexing of the frame interacts with the suspension.

Suspension travel

The severe handling vice of the TR3 and related cars was caused by running out of suspension travel. Other vehicles will run out of suspension travel with some combination of bumps and turns, with similarly catastrophic effect. Excessively modified cars also may encounter this problem.

Tires and wheels

In general softer rubber, higher hysteresis rubber and stiffer cord configurations increase road holding and improve handling. On most types of poor surfaces, large diameter wheels perform better than lower wider wheels. The depth of tread remaining greatly affects aquaplaning (riding over deep water without reaching the road surface). Increasing tire pressures reduces their slip angle, but lessening the contact area is detrimental in usual surface conditions and should be used with caution.

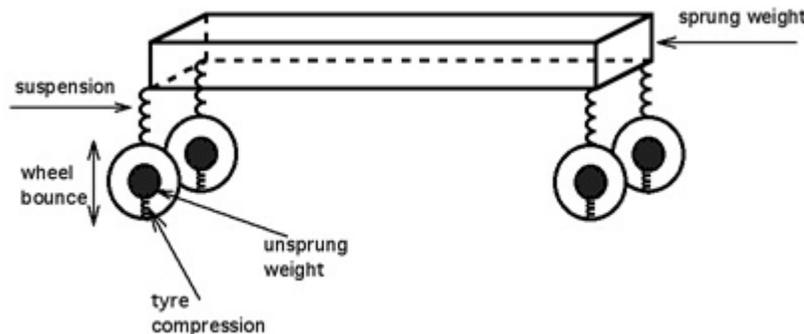
The amount a tire meets the road is an equation between the weight of the car and the type (and size) of its tire. A 1000kg car can depress a 185/65/15 tire more than a 215/45/15 tire longitudinally thus having better linear grip and better braking distance not to mention better aquaplaning performance, while the wider tires having better (dry) cornering resistance.

The contemporary chemical make-up of tires are dependant of the ambient and road temperatures. Ideally a tire should be soft enough to conform to the road surface (thus having good grip), but be hard enough to last for enough duration (distance) to be economically feasible. It is usually a good idea having different set of summer and winter tires for climates having these temperatures.

Track and wheelbase

The axle track provides the resistance to sideways weight transfer and body lean. The wheelbase provides resistance to front/back weight transfer and to pitch angular inertia, and provides the torque lever arm to rotate the car when swerving. The wheelbase, however, is less important than angular inertia (polar moment) to the vehicle's ability to swerve quickly.

Unsprung weight



Ignoring the flexing of other components, a car can be modeled as the sprung weight, carried by the springs, carried by the unsprung weight, carried by the tires, carried by the road. Unsprung weight is more properly regarded as a mass which has its own inherent inertia separate from the rest of the vehicle. When a wheel is pushed upwards by a bump in the road, the inertia of the wheel will cause it to be carried further upward above the height of the bump. If the force of the push is sufficiently large, the inertia of the wheel will cause the tire to completely lift off the road surface resulting in a loss of traction and control. Similarly when crossing into a sudden ground depression, the inertia of the wheel slows the rate at which it descends. If the wheel inertia is large enough, the wheel may be temporarily separated from the road surface before it has descended back into contact with the road surface.

This unsprung weight is cushioned from uneven road surfaces only by the compressive resilience of the tire (and wire wheels if fitted), and which aids the wheel in remaining in

contact with the road surface when the wheel inertia prevents close-following of the ground surface. However, the compressive resilience of the tire results in rolling resistance which requires additional kinetic energy to overcome, and the rolling resistance is expended in the tire as heat due to the flexing of the rubber and steel bands in the sidewalls of the tires. To reduce rolling resistance for improved fuel economy and to avoid overheating and failure of tires at high speed, tires are designed to have limited internal damping.

So the "wheel bounce" due to wheel inertia, or resonant motion of the unsprung weight moving up and down on the springiness of the tire, is only poorly damped, mainly by the dampers or shock absorbers of the suspension. For these reasons, high unsprung weight reduces road holding and increases unpredictable changes in direction on rough surfaces (as well as degrading ride comfort and increasing mechanical loads).

This unsprung weight includes the wheels and tires, usually the brakes, plus some percentage of the suspension, depending on how much of the suspension moves with the body and how much with the wheels; for instance a solid axle is completely unsprung. The main factors that improve unsprung weight are a sprung differential (as opposed to live axle) and inboard brakes. (The De Dion tube suspension operates much as a live axle does, but represents an improvement because the diff is mounted to the body, thereby reducing the unsprung weight.) Aluminum wheels also help. Magnesium alloy wheels are even lighter but corrode easily.

Since only the brakes on the driving wheels can easily be inboard, the Citroën 2CV had inertial dampers on its rear wheel hubs to damp only wheel bounce.

Aerodynamics

Aerodynamic forces are generally proportional to the square of the air speed, therefore car aerodynamics become rapidly more important as speed increases. Like darts, aeroplanes, etc., cars can be stabilised by fins and other rear aerodynamic devices. However, in addition to this cars also use downforce or "negative lift" to improve road holding. This is prominent on many types of racing cars, but is also used on most passenger cars to some degree, if only to counteract the tendency for the car to otherwise produce positive lift.

In addition to providing increased adhesion, car aerodynamics are frequently designed to compensate for the inherent increase in oversteer as cornering speed increases. When a car corners, it must rotate about its vertical axis as well as translate its center of mass in an arc. However, in a tight-radius (lower speed) corner the angular velocity of the car is high, while in a longer-radius (higher speed) corner the angular velocity is much lower. Therefore, the front tires have a more difficult time overcoming the car's moment of inertia during corner entry at low speed, and much less difficulty as the cornering speed increases. So the natural tendency of any car is to understeer on entry to low-speed corners and oversteer on entry to high-speed corners. To compensate for this unavoidable effect, car designers often bias the car's handling toward less corner-entry understeer

(such as by lowering the front roll center), and add rearward bias to the aerodynamic downforce to compensate in higher-speed corners. The rearward aerodynamic bias may be achieved by an airfoil or "spoiler" mounted near the rear of the car, but a useful effect can also be achieved by careful shaping of the body as a whole, particularly the aft areas

In recent years, aerodynamics have become an area of increasing focus by racing teams as well as car manufacturers. Advanced tools such as wind tunnels and computational fluid dynamics (CFD) have allowed engineers to optimize the handling characteristics of vehicles. Advanced wind tunnels such as Wind Shear's Full Scale, Rolling Road, Automotive Wind Tunnel recently built in Concord, North Carolina have taken the simulation of on-road conditions to the ultimate level of accuracy and repeatability under very controlled conditions. CFD has similarly been used as a tool to simulate aerodynamic conditions but through the use of extremely advanced computers and software to duplicate the car's design digitally then "test" that design on the computer.

Delivery of power to the wheels and brakes

The coefficient of friction of rubber on the road limits the magnitude of the vector sum of the transverse and longitudinal force. So the driven wheels or those supplying the most braking tend to slip sideways. This phenomenon is often explained by use of the circle of forces model.

One reason that sports cars are usually rear wheel drive is that power induced oversteer is useful, to a skilled driver, for tight curves. The weight transfer under acceleration has the opposite effect and either may dominate, depending on the conditions. Inducing understeer by applying power in a front wheel drive car is useful via proper use of "Left-foot braking." In any case, this is not an important safety issue, because power is not normally used in emergency situations. Using low gears down steep hills may cause some oversteer.

The effect of braking on handling is complicated by load transfer, which is proportional to the (negative) acceleration times the ratio of the center of gravity height to the wheelbase. The difficulty is that the acceleration at the limit of adhesion depends on the road surface, so with the same ratio of front to back braking force, a car will understeer under braking on slick surfaces and oversteer under hard braking on solid surfaces. Most modern cars combat this by varying the distribution of braking in some way. This is important with a high center of gravity, but it is also done on low center of gravity cars, from which a higher level of performance is expected.

Steering

Depending on the driver, steering force and transmission of road forces back to the steering wheel and the steering ratio of turns of the steering wheel to turns of the road wheels affect control and awareness. Play — free rotation of the steering wheel before the wheels rotate — is a common problem, especially in older model and worn cars. Another is friction. Rack and pinion steering is generally considered the best type of

mechanism for control effectiveness. The linkage also contributes play and friction. Caster — offset of the steering axis from the contact patch — provides some of the self-centering tendency.

Precision of the steering is particularly important on ice or hard packed snow where the slip angle at the limit of adhesion is smaller than on dry roads.

The steering effort depends on the downward force on the steering tires and on the radius of the contact patch. So for constant tire pressure, it goes like the 1.5 power of the vehicle's weight. The driver's ability to exert torque on the wheel scales similarly with his size. The wheels must be rotated farther on a longer car to turn with a given radius. Power steering reduces the required force at the expense of feel. It is useful, mostly in parking, when the weight of a front-heavy vehicle exceeds about ten or fifteen times the driver's weight, for physically impaired drivers and when there is much friction in the steering mechanism.

Four-wheel steering has begun to be used on road cars (Some WW II reconnaissance vehicles had it). It relieves the effect of angular inertia by starting the whole car moving before it rotates toward the desired direction. It can also be used, in the other direction, to reduce the turning radius. Some cars will do one or the other, depending on the speed.

Steering geometry changes due to bumps in the road may cause the front wheels to steer in different directions together or independent of each other. The steering linkage should be designed to minimize this effect.

Electronic stability control

Electronic stability control (ESC) is a computerized technology that improves the safety of a vehicle's stability by attempting to detect and prevent skids. When ESC detects loss of steering control, the system applies individual brakes to help "steer" the vehicle where the driver wants to go. Braking is automatically applied to individual wheels, such as the outer front wheel to counter oversteer, or the inner rear wheel to counter understeer.

The stability control of some cars may not be compatible with some driving techniques, such as power induced over-steer. It is therefore, at least from a sporting point of view, preferable that it can be disabled.

Static alignment of the wheels

Of course things should be the same, left and right, for road cars. Camber affects steering because a tire generates a force towards the side that the top is leaning towards. This is called camber thrust. Additional front negative camber is used to improve the cornering ability of cars with insufficient camber gain.

Rigidity of the frame

The frame may flex with load, especially twisting on bumps. Rigidity is considered to help handling. At least it simplifies the suspension engineers work. Some cars, such as the Mercedes-Benz 300SL have had high doors to allow a stiffer frame.

Driver handling the car

Handling is a property of the car, but different characteristics will work well with different drivers.

Familiarity

A person learns to control a car much as he learns to control his body, so the more he has driven a car or type of car the better it will handle for them. One needs to take extra care for the first few months after buying a car, especially if it differs in design from those they are used to. Other things that a driver must adjust to include changes in tires, tire pressures and load. That is, handling is not just good or bad; it is also the same or different.

Position and support for the driver

Having to take up "g forces" in his/her arms interferes with a driver's precise steering. In a similar manner, a lack of support for the seating position of the driver may cause them to move around as the car undergoes rapid acceleration (through cornering, taking off or braking). This interferes with precise control inputs, making the car more difficult to control.

Being able to reach the controls easily is also an important consideration, especially if a car is being driven hard.

In some circumstances, good support may allow a driver to retain some control, even after a minor accident or after the first stage of an accident.

External conditions that affect handling

Weather

Weather affects handling by changing the amount of available traction on a surface. Different tires do best in different weather. Deep water is an exception to the rule that wider tires improve road holding.

Road condition

Cars with relatively soft suspension and with low unsprung weight are least affected by uneven surfaces, while on flat smooth surfaces the stiffer the better. Unexpected water, ice, oil, etc. are hazards.

Common handling problems

When any wheel leaves contact with the road there is a change in handling, so the suspension should keep all four (or three) wheels on the road in spite of hard cornering, swerving and bumps in the road. It is very important for handling, as well as other reasons, not to run out of suspension travel and "bottom" or "top".

It is usually most desirable to have the car adjusted for a small amount of understeer, so that it responds predictably to a turn of the steering wheel and the rear wheels have a smaller slip angle than the front wheels. However this may not be achievable for all loading, road and weather conditions, speed ranges, or while turning under acceleration or braking. Ideally, a car should carry passengers and baggage near its center of gravity and have similar tire loading, camber angle and roll stiffness in front and back to minimise the variation in handling characteristics. A driver can learn to deal with excessive oversteer or understeer, but not if it varies greatly in a short period of time.

The most important common handling failings are;

- Understeer – the front wheels tend to crawl slightly or even slip and drift towards the outside of the turn. The driver can compensate by turning a little more tightly, but road-holding is reduced, the car's behaviour is less predictable and the tires are liable to wear more quickly.
- Oversteer – the rear wheels tend to crawl or slip towards the outside of the turn more than the front. The driver must correct by steering away from the corner, otherwise the car is liable to spin, if pushed to its limit. Oversteer is sometimes useful, to assist in steering, especially if it occurs only when the driver chooses it by applying power.
- Bump steer – the effect of irregularity of a road surface on the angle or motion of a car. It may be the result of the kinematic motion of the suspension rising or falling, causing toe-in or toe-out at the loaded wheel, ultimately affecting the yaw angle (heading) of the car. It may also be caused by defective or worn out suspension components. This will always happen under some conditions but depends on suspension, steering linkage, unsprung weight, angular inertia, differential type, frame rigidity, tires and tire pressures. If suspension travel is exhausted the wheel either bottoms or loses contact with the road. As with hard turning on flat roads, it is better if the wheel picks up by the spring reaching its neutral shape, rather than by suddenly contacting a limiting structure of the suspension.
- Body roll – the car leans towards the outside of the curve. This interferes with the driver's control, because he must wait for the car to finish leaning before he can

fully judge the effect of his steering change. It also adds to the delay before the car moves in the desired direction. It also slightly changes the weight borne by the tires as described in weight transfer.

- Excessive load transfer – On any vehicle that is cornering, the outside wheels are more heavily loaded than the inside due to the CG being above the ground. Total weight transfer (sum of front and back), in steady cornering, is determined by the ratio of the height of a car's center of gravity to its axle track. When the weight transfer equals half the vehicle's loaded weight, it will start to roll over. This can be avoided by manually or automatically reducing the turn rate, but this causes further reduction in road-holding.
- Slow response – sideways acceleration does not start immediately when the steering is turned and may not stop immediately when it is returned to center. This is partly caused by body roll. Other causes include tires with high slip angle, and yaw and roll angular inertia. Roll angular inertia aggravates body roll by delaying it. Soft tires aggravate yaw angular inertia by waiting for the car to reach their slip angle before turning the car.

Compromises

Ride quality and handling have always been a compromise - technology has over time allowed automakers to combine more of both features in the same vehicle. High levels of comfort are difficult to reconcile with a low center of gravity, body roll resistance, low angular inertia, support for the driver, steering feel and other characteristics that make a car handle well.

For ordinary production cars, manufacturers err towards deliberate understeer as this is safer for inexperienced or inattentive drivers than is oversteer. Other compromises involve comfort and utility, such as preference for a softer smoother ride or more seating capacity.

Inboard brakes improve both handling and comfort but take up space and are harder to cool. Large engines tend to make cars front or rear heavy. In tires, fuel economy, staying cool at high speeds, ride comfort and long wear all tend to conflict with road holding, while wet, dry, deep water and snow road holding are not exactly compatible. A-arm or wishbone front suspension tends to give better handling, because it provides the engineers more freedom to choose the geometry, and more road holding, because the camber is better suited to radial tires, than MacPherson strut, but it takes more space.

The older Live axle rear suspension technology, familiar from the Ford Model T, is still widely used in most sport utility vehicles and trucks, often for the purposes of durability (and cost). The live axle suspension is still used in some sports cars, like the Ford Mustang, and is better for drag racing, but generally has problems with grip on bumpy corners, fast corners and stability at high speeds on bumpy straights.

Aftermarket modifications and adjustments

Lowering the center of gravity will always help the handling (as well as reduce the chance of roll-over). This can be done to some extent by using plastic windows (or none) and light roof, hood (bonnet) and trunk (boot) lid materials, by reducing the ground clearance, etc. Increasing the track with "reversed" wheels will have a similar effect, but remember that the wider the car the less spare room it has on the road and the farther you may have to swerve to miss an obstacle. Stiffer springs and/or shocks, both front and rear, will generally improve handling on close to perfect surfaces, while worsening handling on less-than-perfect road conditions by "skipping" the car (and destroying grip), thus making handling the vehicle difficult. Aftermarket performance suspension kits are usually readily available.

Lighter (mostly aluminum or magnesium alloy) wheels improve handling as well as ride comfort, by lessening unsprung weight.

Moment of inertia can be reduced by using lighter bumpers and wings (fenders), or none at all.

Component	Reduce Under-steer	Reduce Over-steer
Weight distribution	center of gravity towards rear	center of gravity towards front
Front shock absorber	softer	stiffer
Rear shock absorber	stiffer	softer
Front sway bar	softer	stiffer
Rear sway bar	stiffer	softer
Front tire selection ¹	larger contact area ²	smaller contact area
Rear tire selection	smaller contact area	larger contact area ²
Front wheel rim width or diameter	larger ²	smaller
Rear wheel rim width or diameter	smaller	larger ²
Front tire pressure	lower pressure	increase pressure
Rear tire pressure	increase pressure	lower pressure
Front wheel camber	increase negative camber	reduce negative camber
Rear wheel camber	reduce negative camber	increase negative camber

Rear spoiler	smaller	larger
Front height (because these usually affect camber and roll resistance)	lower front end	raise front end
Rear height	raise rear end	lower rear end
Front toe in	decrease	increase
Rear toe in	decrease	increase
<p>1) Tire contact area can be increased by using wider tires, or tires with fewer grooves in the tread pattern. Of course fewer grooves has the opposite effect in wet weather or other poor road conditions.</p> <p>2) These also improve road holding, under most conditions.</p>		

Cars with unusual handling problems

Certain vehicles can be involved in a disproportionate share of single-vehicle accidents; their handling characteristics may play a role:

- Early Porsche 911s — suffered from treacherous lift off oversteer (where the rear of the car loses grip as the driver lifts off the accelerator); also the inside front wheel leaves the road during hard cornering on dry pavement, causing increasing understeer. The roll bar stiffness at the front is set to compensate for the rear-heaviness and gives neutral handling in ordinary driving. This compensation starts to give out when the wheel lifts. A skilled driver can use the 911's other features to his/her advantage, making the 911 an extremely capable sports car in expert hands. Later 911s have had increasingly sophisticated rear suspensions and larger rear tires, eliminating these problems.
- Triumph TR2, and TR3 — began to oversteer more suddenly when their inside rear wheel lifted.
- Volkswagen Beetle — (original Beetle) sensitivity to crosswinds, due to the lightness of the front of the rear engine car; and poor roll stability due to the swing axle suspension. People who drove them hard fitted reversed wheels and bigger rear tires and rims to ameliorate.
- Chevrolet Corvair - cited for dangerous handling in *Unsafe at Any Speed* caused by poor roll stability due to the swing axle rear suspension similar to that used in the Volkswagen Beetle. These problems were corrected with the redesign of the Corvair for 1965, however, it died from its negative publicity.
- The large, rear-engine Tatra (known as the 'Czech secret weapon') killed so many Nazi officers during World War II that the German Army eventually forbade its officers from driving the Tatra.
- Some 1950s American "full size" cars responded very slowly to steering changes because of their very large angular inertia, softly tuned suspension which made

- ride quality a priority over cornering, and comfort oriented cross bias tires. *Auto Motor und Sport* reported on one of these that they lacked the courage to test it for top speed, probably due to their familiarity with smaller European cars and their unfamiliarity with large American cars.
- Dodge Omni and Plymouth Horizon — these early American responses to the Volkswagen Rabbit were found "unacceptable" in their initial testing by Consumer Reports, due to an observed tendency to display an uncontrollable oscillating yaw from side to side under certain steering inputs. While Chrysler's denials of this behaviour were countered by a persistent trickle of independent reports of this behaviour, production of the cars was altered to equip them with both a lighter weight steering wheel and a steering damper, and no further reports of this problem were heard.
 - The Suzuki Samurai — was similarly reported by Consumer Reports to exhibit a propensity to tipping over onto two wheels, to the point where Consumer Reports claimed they were afraid to continue testing the vehicle without the attachment of outrigger wheels to catch it from completely rolling over. In its first set of tests, the Samurai performed well. R. David Little, Consumers Union's technical director, drove the light SUV through several short, hard turns, designed to simulate an emergency, such as trying to avoid a child running in front of the car. An article published several years later in a Consumer Reports anniversary issue prompted Suzuki to sue. The suit was based on the perception that Consumer Reports rigged the results: "This case is about lying and cheating by Consumers Union for its own financial motives," George F. Ball, Suzuki's managing counsel, said Monday. "They were in debt [in 1988], and they needed a blockbuster story to raise and solicit funds." Entrepreneur Magazine reported that "Suzuki's case centered on a change CU made while testing the vehicle. After the Samurai and other SUVs completed the standard course without threatening to roll over, CU altered the course to make the turns more abrupt. The other vehicles didn't show a problem, but the Samurai tipped up and would have rolled over but for outriggers set up to prevent that outcome" After eight years in court the parties consented to a settlement which did not include monetary damages nor a retraction.. Commenting on the settlement, Consumer Union said,"Consumers Union also says in the agreement that it "never intended to imply that the Samurai easily rolls over in routine driving conditions." CU Vice President of Technical Policy further stated: "There is no apology. "We stand fully behind our testing and rating of the Samurai." In a joint press statement Suzuki recognized "CU's stated commitment for objective and unbiased testing and reporting."
 - Mercedes-Benz A-Class — a tall car with a high center of gravity; early models showed excessive body roll during sharp swerving manoeuvres and rolled over, most particularly during the Swedish moose test. This was later corrected using Electronic Stability Control and retrofitted at great expense to earlier cars.
 - Ford Explorer — a dangerous tendency to blow a rear tire and flip over. Ford had constructed a vehicle with a high center of gravity - the tendency to roll over on sharp changes in direction is built in to the vehicle. Ford attempted to counteract the forces of nature by specifying lower than optimum pressures, in the tires in

order to induce them to lose traction and slide under sideways forces rather than to grip and force the vehicle to roll over. For reasons that were never entirely clear, tires from one factory tended to blow out when under inflated, these vehicles then rolled over, which led to a spate of well publicized single-vehicle accidents.

Ford and Firestone, the makers of the tires, pointed fingers at each other, with the final blame being assigned to quality control practices at a Firestone plant which was undergoing a strike. Tires from a different Firestone plant were not associated with this problem. An internal document dated 1989 states

Engineering has recommended use of tire pressures below maximum allowable inflation levels for all UN46 tires. As described previously, the reduced tire pressures increase understeer and reduce maximum cornering capacity (both 'stabilising' influences). This practice has been used routinely in heavy duty pick-up truck and car station wagon applications to assure adequate understeer under all loading conditions. Nissan (Pathfinder), Toyota, Chevrolet, and Dodge also reduce tire pressures for selected applications. While we cannot be sure of their reasons, similarities in vehicle loading suggest that maintaining a minimal level of understeer under rear-loaded conditions may be the compelling factor.

This contributed to build-up of heat and tire deterioration under sustained high speed use, and eventual failure of the most highly stressed tire. Of course, the possibility that slightly substandard tire construction and slightly higher than average tire stress, neither of which would be problematic in themselves, would in combination result in tire failure is quite likely. The controversy continues without unequivocal conclusions, but it also brought public attention to a generally high incidence of rollover accidents involving SUVs, which the manufacturers continue to address in various ways. A subsequent NHTSA investigation of real world accident data showed that the SUVs in question were no more likely to roll over than any other SUV, after a tread separation.

- The Jensen GT (hatchback coupe) — was introduced in attempt to broaden the sales base of the Jensen Healey, which had up to that time been a roadster or convertible. Its road test report in *Motor Magazine* and a very similar one, soon after, in *Road & Track* concluded that it was no longer fun enough to drive to be worth that much money. They blamed it on minor suspension changes. Much more likely, the change in weight distribution was at fault. The Jensen Healey was a rather low and wide fairly expensive sports car, but the specifications of its suspension were not particularly impressive, having a solid rear axle. Unlike the AC Ace, with its double transverse leaf rear suspension and aluminium body, the Jensen Healey could not stand the weight of that high up metal and glass and still earn a premium price for its handling. The changes also included a cast iron exhaust manifold replacing the aluminium one, probably to partly balance the high and far back weight of the top. The factory building was used to build multi-tub truck frames.
- The rear engined Renault Dauphine earned in Spain the sobriquet of the "*widow's car*", due to its bad handling.

- Three-wheeled cars/vehicles have unique handling issues, especially considering whether the single wheel is at the front or back. (Motorcycles with sidecars; another matter.) Buckminster Fuller's Dymaxion car caused a sensation, but ignorance of the problems of rear-wheel-steering led to a fatal crash that destroyed its reputation.