Automotive Handling and Technology

Arjun Applegate

First Edition, 2012

ISBN 978-81-323-2933-6

Published by:
Orange Apple
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1

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". 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: $I = M(height^2 + width^2) / 12$.

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.

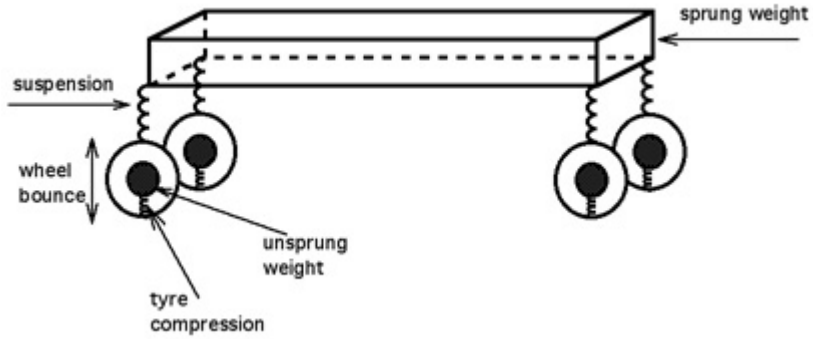
The amount a tire meets the road is an equation between the weight of the car and the type (and size) of its tire. A 1000kg car can depress a 185/65/15 tire more than a 215/45/15 tire longitudenally thus having better linear grip and better braking distance not to mention better aquaplaning performance,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

2) These also improve road holding, under most conditions.

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) senstitivity 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.

Chapter 2

Downforce

Three different styles of front wings from three different Formula One eras, all designed to produce downforce at the front end of the respective race cars. *Top to bottom:* Ferrari 312 (1979), Lotus 79 (1978), McLaren MP4-10 (1995)

Downforce is a downwards thrust created by the aerodynamic characteristics of a car. The purpose of downforce is to allow a car to travel faster through a corner by increasing the vertical force on the tires, thus creating more grip.

Fundamental principles

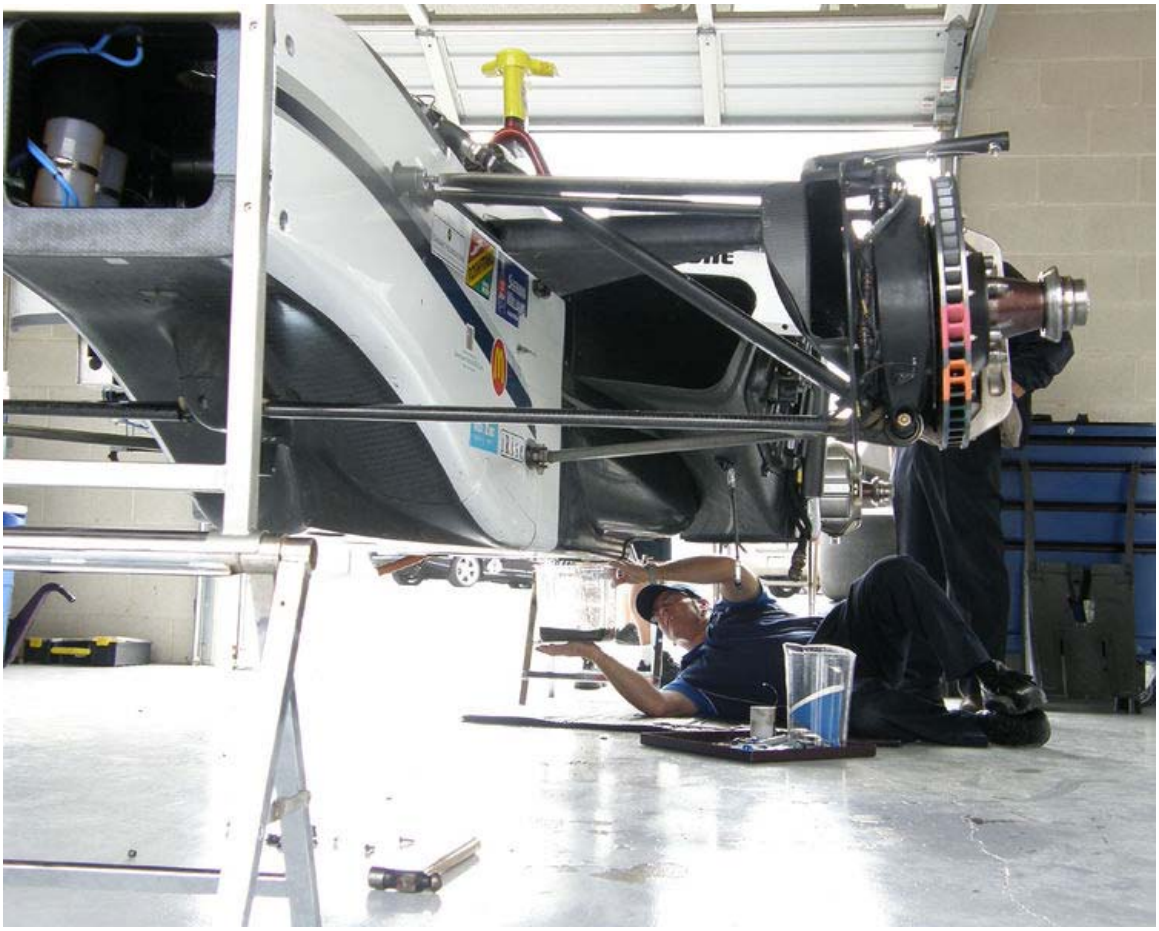
The same principle that allows an airplane to rise off the ground by creating lift from its wings is used in reverse to apply force that presses the race car against the surface of the track. This effect is referred to as "aerodynamic grip" and is distinguished from "mechanical grip," which is a function of the car mass repartition, tires and suspension. The creation of downforce by passive devices almost always can only be achieved at the cost of increased aerodynamic drag (or friction), and the optimum setup is almost always a compromise between the two. The aerodynamic setup for a car can vary considerably between race tracks, depending on the length of the straights and the types of corners; some drivers also make different choices on setup. Because it is a function of the flow of air over and under the car, and because aerodynamic forces increase with the square of velocity, downforce increases with the square of the car's speed and requires a certain minimum speed in order to produce a significant effect. But some cars have had rather unstable aerodynamics, such that a minor change in angle of attack or height of the vehicle and this can cause large changes in the downforce. In the very worse cases the can cause the car to experience lift, not downforce, for example, caused by a bump on the track or slipstreaming over a crest, and sometimes can have disastrous consequences. A notorious example of this was Peter Dumbreck's Mercedes-Benz CLR in the 1999 Le Mans 24 hours, which flipped spectacularly after closely following a competitor car over a hump.

Two primary components of a racing car can be used to create downforce when the car is travelling at racing speed:

- the shape of the body, and
- the use of airfoils.

Most racing formulae have a ban on aerodynamic devices that can be adjusted during a race, except at pit stops.

The bottom panel of the Panoz DP01 ChampCar exhibiting complex aerodynamic design.



The underside curves of the Panoz DP01 ChampCar.

The formula for downforce of a wing is given by:

$$D = \frac{1}{2} \times (WS \times \ H \times \ AoA) \times F \times \rho \times V^2$$

Where:

- D is downforce in newtons
- WS is wingspan in metres
- H is height in metres
- AoA is angle of attack
- F is drag coefficient
- ρ is air density in kg/m³
- V is velocity in m/s

Body

The rounded and tapered shape of the top of the car is designed to slice through the air and minimize wind resistance. Detailed pieces of bodywork on top of the car can be added to allow a smooth flow of air to reach the downforce-creating elements (i.e., wings or spoilers, and underbody tunnels).

The overall shape of a street car resembles an airplane wing with air flowing over it faster than the air flows under it causing a difference in air pressure. Almost all street cars have aerodynamic lift as a result of this shape. There are many techniques that are used to counter-balance a street car. Looking at the profile of most street cars, the front bumper has the lowest ground clearance followed by the section between the front and rear tires, and followed yet by a rear bumper usually with the highest clearance. Using this method, the air flowing under the front bumper will make its way back to the rear bumper where it has a larger volume and thus a lower pressure. Race cars will exemplify this effect by adding a rear diffuser to better control the pressures directly under the rear bumper. Other aerodynamic components can be found on the underside to improve downforce and/or reduce drag include a splitter and a diffuser and vortex generators.

Airfoils

The amount of downforce created by the wings or spoilers on a car is dependent primarily on two things:

- The shape, including surface area, aspect ratio and cross-section of the device, and
- The device's orientation (or angle of attack).

A larger surface area creates greater downforce and greater drag (also known as air resistance). The aspect ratio is the width of the airfoil divided by its depth. The aspect ratio formula is written like AR=b squared/s, where AR=aspect ratio, b=spand squared, and s=wing area. Also, a greater angle of attack (or tilt) of the wing or spoiler, creates more downforce, which puts more pressure on the rear wheels and more drag.

The rear wing of a 1998 Formula One car, with three aerodynamic elements (1, 2, 3). The rows of holes for adjustment of the angle of attack (4) and installation of another element (5) are visible on the wing's endplate.

Front

The function of the airfoils at the front of the car is twofold. They create downforce that enhances the grip of the front tires, while also optimizing (or minimizing disturbance to) the flow of air to the rest of the car. The front wings on an open-wheeled car undergo constant modification as data is gathered from race to race, and are customized for every characteristic of a particular circuit. In most series, the wings are even designed for adjustment during the race itself when the car is serviced.

Rear

The flow of air at the rear of the car is affected by the front wings, front wheels, mirrors, driver's helmet, side pods and exhaust. This causes the rear wing to be less aerodynamically efficient than the front wing, Yet, because it must generate more than twice as much downforce as the front wings in order to maintain the handling to balance the car, the rear wing typically has a much larger aspect ratio, and often uses two or more elements to compound the amount of downforce created. Like the front wings, each of these elements can often be adjusted when the car is serviced, before or even during a race, and are the object of constant attention and modification.

Wings in unusual places

Partly as a consequence of rules aimed at reducing downforce from the front and rear wings of F1 cars, several teams have sought to find other places to position wings. Small wings mounted on the rear of the cars' sidepods began to appear in mid-1994, and were virtually standard on all F1 cars in one form or another, until all such devices were outlawed in 2009. Other wings have sprung up in various other places about the car, but these modifications are usually only used at circuits where downforce is most sought, particularly the twisty Hungary and Monaco racetracks.

The 1995 McLaren Mercedes MP4/10 was one of the first cars to feature a "midwing", using a loophole in the regulations to mount a wing on top of the engine cover. This arrangement has since been used by every team on the grid at one time or another, and in the 2007 Monaco Grand Prix all but two teams used them. These midwings are not to be confused either with the roll-hoop mounted cameras which each car carries as standard in all races, or with the bull-horn shaped flow controllers first used by McLaren and since by BMW Sauber, whose primary function is to smooth and redirect the airflow in order to make the rear wing more effective rather than to generate downforce themselves.

A variation on this theme was "X-wings", high wings mounted on the front of the sidepods which used a similar loophole to midwings. These were first used by Tyrrell in

1997, and were last used in the 1998 San Marino Grand Prix, by which time Ferrari, Sauber, Jordan and others had used such an arrangement. However it was decided they would have to be banned in view of the obstruction they caused during refueling and the risk they posed to the driver should a car roll over. (It is rumored that Bernie Ecclestone saw them as being too ugly on television and therefore had them banned.)

Various other extra wings have been tried from time to time, but nowadays it is more common for teams to seek to improve the performance of the front and rear wings by the use of various flow controllers such as the afore-mentioned "bull-horns" used by McLaren.

Chapter 3

Inboard Brake and Oversteer

Inboard brake

An **inboard braking system** is an automobile technology wherein the brakes are mounted between the bearings of the wheels that constitute an axle.

Excepting the case of vehicles with beam axles and vehicles having no suspension, in practice it is normal for inboard brakes to be mounted rigidly with respect to the body of the vehicle, often to the differential casing. This is done to move the weight of the braking mechanism from being carried by the wheels directly (unsprung weight), to being carried indirectly by the wheels via the suspension (sprung mass). This then necessitates a means of transferring braking torque from the brake mechanism to the wheel, which is capable of operating despite the relative movement between body and wheel. Driven wheels already have shafting (or in older vehicles chains) which serve this purpose so there is no penalty for them, but undriven wheels require a similar mechanism which is then called a brake shaft.

The benefit of such a system is primarily the reduction of unsprung weight which improves handling and ride. The suspension does not have to resist twisting when the brakes are applied. The wheels don't enclose the brake mechanism allowing greater flexibility in wheel offset, and placement of suspension members. It is also much easier to protect the brake mechanism from the outside environment, and protect it from water, dust, and oil. Of secondary importance is flexible brake pipes are avoided and rigid pipes allow increases in brake fluid pressure, allowing a smaller disks for a given braking torque.

The mechanical disadvantages are largely those of added complexity. Undriven wheels require a brake shaft. It is more difficult to arrange for cooling air to flow over the wheel, and air ducting can be required, to prevent brake fade.

There can be practical difficulties,in servicing the brake mechanism. Instead of simply removing a wheel to renew pads and discs, the vehicle may need to be jacked up, so a

mechanic can work underneath the vehicle. Additionally renewing brake discs can require dismantling the half axle. This greatly discourages their use in motorsport, and the additional time makes for greater labour cost when servicing these parts.

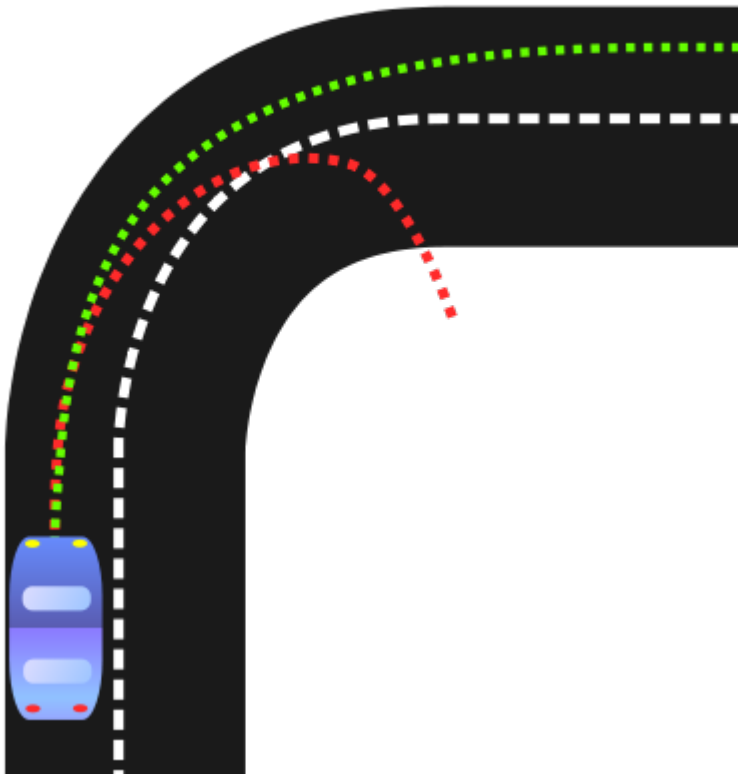
This system was more common in the 1960s, found on such cars as the Jaguar E-Type and Citroën 2CV. The Hummer H1 is one of the few modern vehicles fitted with inboard brakes, to accommodate each wheel's portal gear system.

Hybrid gasoline/electric vehicles may be considered to have partial inboard braking, because the devices used for the regenerative part of the braking are usually mounted inboard.

Cars with inboard brakes

- Alfa Romeo Alfasud Alfetta GTV GTV6 Giulietta 75 90 SZ Milano
- Audi 100 LS
- British Racing Motors: Some BRM racing cars had a single inboard disk brake, acting on both back wheels.
- Citroën 2CV, DS, GS, SM, Ami, Dyane, Axel and other Citroën models
- DKW Junior plus other models
- Hummer H1
- Jaguar E-Type, Jaguar XJ (until XJ40), Jaguar XJ-S
- Lancia Aurelia
- Lotus 72 Formula One racing car
- Lotus Elite, Elan and Esprit
- Mercedes-Benz W196 and 300SLR
- Monteverdi Hai 450 SS
- Oldsmobile Toronado
- Oltcit
- Rover P6
- Subaru G

Oversteer



Oversteer

Oversteer is a term for a car handling condition in which the slip angle of the rear tires is greater than the slip angle of the front tires. In other words, the amount that the car *steers* is *over* that commanded by the driver. The effect is opposite to that of understeer.

An oversteering car is referred to as "loose" or "free". Oversteer is a dynamically unstable condition; in other words, if control is lost, the vehicle will spin.

Causes

The tendency of a car to oversteer is affected by several factors such as mechanical traction, aerodynamics and suspension, and driver control, and may be applicable at any level of lateral acceleration. Generally, oversteer is the condition when the slip angle of the rear tires exceeds that of the front tires, even when they are both small. *Limit oversteer* occurs when the rear tires reach the limits of their lateral traction during a

cornering situation but the front tires have not, thus causing the rear of the vehicle to head towards the outside of the corner. The driving technique called opposite lock is meant to cope in this circumstance. *Trailing Throttle Oversteer* (TTO), a.k.a. "snap-oversteer" is induced by the weight balance of the car shifting from the rear to the front, this may happen if the car is cornering under throttle, causing the car to settle on the rear, if the throttle application would be removed—e.g. as to reduce the radius of the turn—the balance would suddenly shift to the front, giving less traction on the rear, if the car was already at the traction limit before the driver lifted the throttle it is very likely to cause a TTO. Rear wheel drive cars are more prone to oversteer, in particular when applying power in a tight corner. This occurs because the rear tires must handle both the lateral cornering force and engine torque.

Yaw rate

The terms oversteer and understeer are related to yaw rate and not to *sideways movement*. A car undergoes a circular spinning motion (yaw) as it turns, as well as *sideways movement* (towards the inside of the corner). Understeer and oversteer refer to the yaw motion. The difference between yaw and sideways movement is best demonstrated by practising turning an aircraft, because separate controls control each of the two movement types in aircraft. Consider a car with its steering wheel turned part way to one side and locked in that position. Now imagine that car rolling forward very slowly on a flat surface. It will move along an arc of a circle whose radius is determined solely by the position of the wheels, since centrifugal force is minimal. Its sideways motion and yaw rate are hence interlinked and set by the steering wheel position. However, the wheels can only provide a limited amount of sideways force before they slide. This sliding will happen at a larger radius as either the speed increases, the friction coefficient decreases, or the normal force decreases. Once this sliding occurs, the sideways movement and yaw rate may become unlinked. If the yaw rate of the car tends towards a larger radius than the radius set by the wheels, it is said to understeer. If the yaw rate radius is smaller (spinning too fast), it is called oversteer. During oversteer or understeer the sideways movement of the car may also follow a different radius to that set by the steering wheel, but this does not affect the definition of oversteer or understeer.

Critical speed

Oversteering cars have an associated instability mode, which occurs at and above the critical speed. As this speed is approached, with the car on an approximately straight course, the steering becomes progressively more sensitive. At the critical speed the yaw velocity gain becomes infinite, that is, the car will turn violently in response to the slightest steering input or external disturbance. Above the critical speed analysis shows that the yaw response will be reversed for a given steering wheel input, such as a car turning left in response to turning the wheel to the right. This is an oversimplification, however, as the model used is linearised in many important ways. Understeering cars do not suffer from this, which is one of the reasons why high speed cars tend to be set up to understeer.

In road cars

A Mercedes-Benz CLS AMG 55 oversteering on a wet surface

Contrary to popular opinion, modern rear-wheel-drive cars are much more user-friendly in regard to oversteer. Their suspension is not balanced heavily toward understeer, in fact with today's experience in making cars, most manufacturers try to achieve neutrality from the respective configurations so that they are largely capable of oversteering especially when the driver attempts to invoke it on purpose.

The natural reaction of most drivers to the perception of loss of control during oversteer is to immediately lift their foot off the gas pedal. Cutting the power mid-corner can induce more oversteer, known as lift-off oversteer. The correct reaction to oversteer is to gently steer into the slide and take the power away as needed without pitching the car forward. Indeed, "trail braking", or continuing to apply brake pressure after turning into a curve, can induce oversteer by transferring weight off the rear tires, regardless of whether the car is front, rear or all-wheel drive.

Braking may or may not improve the situation. Most modern cars have a brake bias which tends to straighten out the car. However, there are two factors working against this. Most drivers must lift their foot from the gas pedal in order to press the brake, inducing the spin as described above. The second is that braking transfers more of the vehicle's weight forward which tends to worsen oversteer. Even so, the brake bias may be enough to help or at least not make it worse.

In race cars

A car that tends neither to oversteer nor understeer when pushed to the limit is said to have neutral handling. It seems intuitive that race drivers would prefer a slight oversteer condition to rotate the car around a corner, but this isn't usually the case for two reasons. Accelerating early as the car passes the apex of a corner allows it to gain extra speed down the following straight. The driver who accelerates sooner and/or harder has a large advantage. The rear tires need some excess traction to accelerate the car in this critical phase of the corner, while the front tires can devote all their traction to turning. So the car must be set up with a slight understeer or "tight" tendency. Also, an oversteering car tends to be twitchy and ill tempered, making a race car driver more likely to lose control during a long race or when reacting to sudden situations in traffic.

Carroll Smith, in his book "Drive to Win", provides a detailed explanation of why a fast race car must have a bit of understeer. Note that this applies only to road racing. Dirt racing is a different matter.

Even so, some successful race car drivers do prefer a bit of oversteer in their cars, preferring a car which is less sedate and more willing to turn into corners (or inside their opponents). The judgement of a car's handling balance is not an objective one. Driving style is a major factor in the apparent balance of a car. This is why two drivers with identical cars on the same race team often run with rather different balance settings from each other. And both may call the balance of their cars 'neutral'.

Aerodynamic stability

The importance of the position of a fast car's aerodynamic centre of pressure to its directional stability was not understood at first. In the late 1950s, cars such as the 120 mph Jaguar 3.4-litre saloon / sedan were reported to feel directionally unstable at high speeds, and were badly affected by gusts.

Simple streamlining tends to lift the back of a car, reducing the downforce on its back wheels relative to the front wheels, resulting in oversteer. Streamlining also moves the centre of pressure well forward, causing directional instability in cross winds.

At first, aerodynamic oversteer was counteracted by setting the cars up with strong mechanical understeer, resulting in excessive understeer at lower speeds. Various means of achieving aerodynamic stability have since been developed, such as tail fins to move the centre of pressure back, the Kamm tail and the spoiler to reduce lift, rear wings to generate downward acting lift force, and air dams and skirts to reduce air pressure under the car, causing down force due to ground effect. Most of those features improve stability but increase drag, reducing top speed and increasing fuel consumption. However an early example of a fin used for directional stability without reducing top speed is provided by the Jaguar D-Type.

Usually these features are little more than styling gimmicks, the cars not being fast enough to benefit from them.

In modern race cars, especially open-wheel race cars, oversteering in high speed turns is caused mainly by aerodynamic configuration. A heavier aerodynamic load on the front of the car relative to the rear causes it to oversteer. Oversteer in low speed turns is often reduced or eliminated electronically through traction control (if the sanctioning body allows their use). The front/rear balance required to make the cars fast through corners is obtained by setting up the aerodynamics and balancing the suspension. The car's tendency toward oversteer is generally increased by softening the front suspension or stiffening the rear suspension in roll. The suspension's roll stiffness may be adjusted independently of pitch stiffness by means of adjustable or interchangeable anti-roll bars at one or both ends of the car. Camber angle, ride height, and tire pressures can also be used to tune the balance of the car.

Chapter 4

Steering

Steering is the term applied to the collection of components, linkages, etc. which will allow a vessel (ship, boat) or vehicle (car, motorcycle, bicycle) to follow the desired course. An exception is the case of rail transport by which rail tracks combined together with railroad switches (and also known as 'points' in British English) provide the steering function.

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

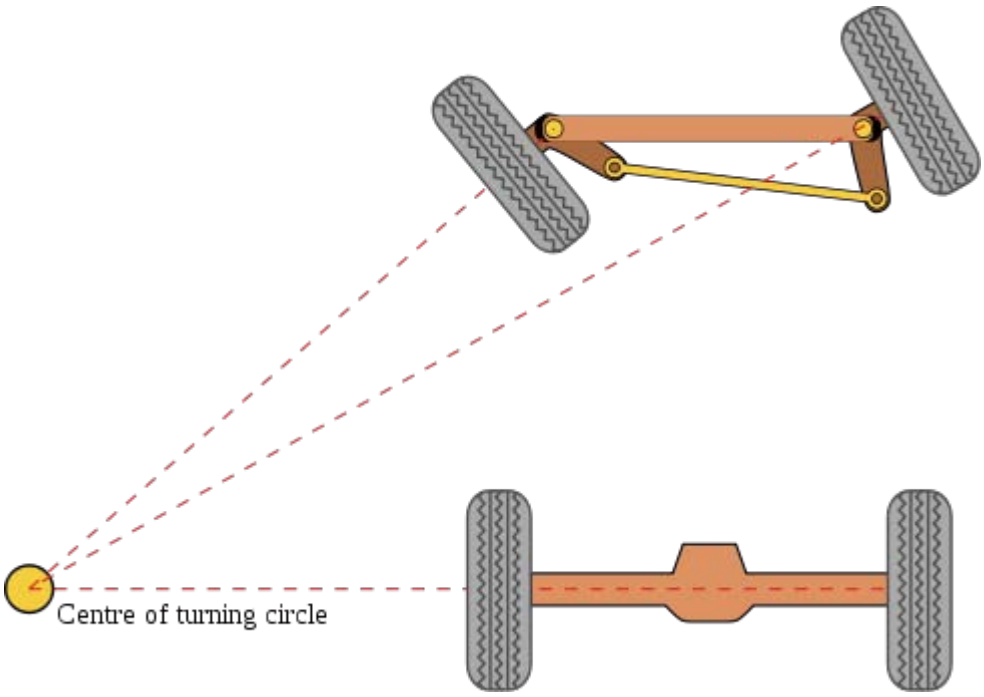
Introduction

The most conventional steering arrangement is to turn the front wheels using a hand–operated steering wheel which is positioned in front of the driver, via the steering column, which may contain universal joints (which may also be part of the collapsible steering column design), to allow it to deviate somewhat from a straight line. Other arrangements are sometimes found on different types of vehicles, for example, a tiller or rear–wheel steering. Tracked vehicles such as tanks usually employ differential steering — that is, the tracks are made to move at different speeds or even in opposite directions to bring about a change of course or direction.

Wheeled vehicle steering

Basic geometry

The basic aim of steering is to ensure that the wheels are pointing in the desired directions. This is typically achieved by a series of linkages, rods, pivots and gears. One of the fundamental concepts is that of *caster angle*- each wheel is steered with a pivot point ahead of the wheel; this makes the steering tend to be self-centering towards the direction travel.

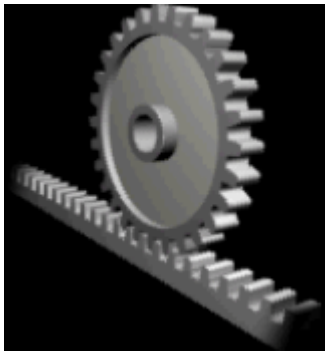


Ackermann steering geometry

The steering linkages connecting the steering box and the wheels usually conforms to a variation of Ackermann steering geometry, to account for the fact that in a turn, the inner

wheel is actually travelling a path of smaller radius than the outer wheel, so that the degree of toe suitable for driving in a straight path is not suitable for turns.

Rack and pinion, recirculating ball, worm and sector



Rack and pinion

Rack and pinion unit mounted in the cockpit of an Ariel Atom sports car chassis. For most high volume production, this is usually mounted on the other side of this panel

Many modern cars use rack and pinion steering mechanisms, where the steering wheel turns the pinion gear; the pinion moves the rack, which is a linear gear that meshes with

the pinion, converting circular motion into linear motion along the transverse axis of the car (side to side motion). This motion applies steering torque to the swivel pin ball joints that replaced previously used kingpins of the stub axle of the steered wheels via tie rods and a short lever arm called the steering arm.

The rack and pinion design has the advantages of a large degree of feedback and direct steering "feel". A disadvantage is that it is not adjustable, so that when it does wear and develop lash, the only cure is replacement.

Older designs often use the recirculating ball mechanism, which is still found on trucks and utility vehicles. This is a variation on the older worm and sector design; the steering column turns a large screw (the "worm gear") which meshes with a sector of a gear, causing it to rotate about its axis as the worm gear is turned; an arm attached to the axis of the sector moves the Pitman arm, which is connected to the steering linkage and thus steers the wheels. The recirculating ball version of this apparatus reduces the considerable friction by placing large ball bearings between the teeth of the worm and those of the screw; at either end of the apparatus the balls exit from between the two pieces into a channel internal to the box which connects them with the other end of the apparatus, thus they are "recirculated".

The recirculating ball mechanism has the advantage of a much greater mechanical advantage, so that it was found on larger, heavier vehicles while the rack and pinion was originally limited to smaller and lighter ones; due to the almost universal adoption of power steering, however, this is no longer an important advantage, leading to the increasing use of rack and pinion on newer cars. The recirculating ball design also has a perceptible lash, or "dead spot" on center, where a minute turn of the steering wheel in either direction does not move the steering apparatus; this is easily adjustable via a screw on the end of the steering box to account for wear, but it cannot be entirely eliminated because it will create excessive internal forces at other positions and the mechanism will wear very rapidly. This design is still in use in trucks and other large vehicles, where rapidity of steering and direct feel are less important than robustness, maintainability, and mechanical advantage. The much smaller degree of feedback with this design can also sometimes be an advantage; drivers of vehicles with rack and pinion steering can have their thumbs broken when a front wheel hits a bump, causing the steering wheel to kick to one side suddenly (leading to driving instructors telling students to keep their thumbs on the front of the steering wheel, rather than wrapping around the inside of the rim). This effect is even stronger with a heavy vehicle like a truck; recirculating ball steering prevents this degree of feedback, just as it prevents desirable feedback under normal circumstances.

The worm and sector was an older design, used for example in Willys and Chrysler vehicles, and the Ford Falcon (1960s).

Other systems for steering exist, but are uncommon on road vehicles. Children's toys and go karts often use a very direct linkage in the form of a bellcrank (also commonly known as a Pitman arm) attached directly between the steering column and the steering arms,

and the use of cable-operated steering linkages (e.g. the Capstan and Bowstring mechanism) is also found on some home-built vehicles such as soapbox cars and recumbent tricycles.

Power steering

Power steering, assists the driver of an automobile in steering by directing a portion of the vehicle's power to traverse the axis of one or more of the roadwheels. As vehicles have become heavier and switched to front wheel drive, particularly using negative offset geometry, along with increases in tire width and diameter, the effort needed to turn the steering wheel manually has increased — often to the point where major physical exertion is required. To alleviate this, auto makers have developed power steering systems: or more correctly power-assisted steering — on road going vehicles there has to be a mechanical linkage as a fail safe. There are two types of power steering systems— hydraulic and electric/electronic. A hydraulic-electric hybrid system is also possible.

A hydraulic power steering (HPS) uses hydraulic pressure supplied by an engine-driven pump to assist the motion of turning the steering wheel. Electric power steering (EPS) is more efficient than the hydraulic power steering, since the electric power steering motor only needs to provide assistance when the steering wheel is turned, whereas the hydraulic pump must run constantly. In EPS, the assist level is easily tunable to the vehicle type, road speed, and even driver preference. An added benefit is the elimination of environmental hazard posed by leakage and disposal of hydraulic power steering fluid. Also in the event of the engine cutting out, assist will not be lost - whereas hydraulic will stop working, as well as making the steering doubly heavy as the driver has to turn the power-assist mechanism on top of the steering system itself.

Speed Sensitive Steering

An outgrowth of power steering is speed sensitive steering, where the steering is heavily assisted at low speed and lightly assisted at high speed. The auto makers perceive that motorists might need to make large steering inputs while manoeuvering for parking, but not while traveling at high speed. The first vehicle with this feature was the Citroën SM with its Diravi layout, although rather than altering the amount of assistance as in modern power steering systems, it altered the pressure on a centring cam which made the steering wheel try to "spring" back to the straight-ahead position. Modern speed-sensitive power steering systems reduce the mechanical or electrical assistance as the vehicle speed increases, giving a more direct feel. This feature is gradually becoming more common.

Four-wheel steering

Four-wheel steering (or all-wheel steering) is a system employed by some vehicles to improve steering response, increase vehicle stability while maneuvering at high speed, or to decrease turning radius at low speed.

Sierra Denali with Quadrasteer, rear steering angle

In most *active* four-wheel steering systems, the rear wheels are steered by a computer and actuators. The rear wheels generally cannot turn as far as the front wheels. Some systems, including Delphi's Quadrasteer and the system in Honda's Prelude line, allow the rear wheels to be steered in the opposite direction as the front wheels during low speeds. This allows the vehicle to turn in a significantly smaller radius — sometimes critical for large trucks or tractors and vehicles with trailers.

Many modern vehicles offer a form of *passive* rear steering to counteract normal vehicle tendencies. For example, Subaru used a passive steering system to correct for the rear wheel's tendency to toe-out. On many vehicles, when cornering, the rear wheels tend to steer slightly to the outside of a turn, which can reduce stability. The passive steering system uses the lateral forces generated in a turn (through suspension geometry) and the bushings to correct this tendency and steer the wheels slightly to the inside of the corner. This improves the stability of the car, through the turn. This effect is called compliance understeer and it, or its opposite, is present on all suspensions. Typical methods of achieving compliance understeer are to use a Watt's Link on a live rear axle, or the use of toe control bushings on a twist beam suspension. On an independent rear suspension it is normally achieved by changing the rates of the rubber bushings in the suspension. Some suspensions will always have compliance oversteer due to geometry, such as Hotchkiss live axles or a semi-trailing arm IRS.

Passive rear wheel steering is not a new concept, as it has been in use for many years, although not always recognised as such. For example, Jaguar independent rear suspension incorporated a small amount of passive rear wheel steering since 1961.

Recent application

In an active four-wheel steering system, all four wheels turn at the same time when the driver steers. There can be controls to switch off the rear steer and options to steer only the rear wheel independent of the front wheels. At slow speeds (*e.g.* parking) the rear wheels turn opposite of the front wheels, reducing the turning radius by up to twenty-five percent, while at higher speeds both front and rear wheels turn alike (electronically controlled), so that the vehicle may change position with less yaw, enhancing straight-line stability. The "Snaking effect" experienced during motorway drives while towing a travel trailer is thus largely nullified. Four-wheel steering found its most widespread use in monster trucks, where maneuverability in small arenas is critical, and it is also popular in large farm vehicles and trucks. Some of the modern European Intercity buses also utilize four-wheel steering to assist maneuverability in bus terminals, and also to improve road stability.

General Motors offers Delphi's Quadrasteer in their consumer Silverado/Sierra and Suburban/Yukon. However, only 16,500 vehicles have been sold with this system since its introduction in 2002 through 2004. Due to this low demand, GM discontinued the technology at the end of the 2005 model year.

Previously, Honda had four-wheel steering as an option in their 1987-2000 Prelude, and Mazda also offered four-wheel steering on the 626 and MX6 in 1988.

A new "Active Drive" system is introduced on the 2008 version of the Renault Laguna line. It was designed as one of several measures to increase security and stability. The Active Drive should lower the effects of under steer and decrease the chances of spinning by diverting part of the G-forces generated in a turn from the front to the rear tires. At low speeds the turning circle can be tightened so parking and maneuvering is easier.

Articulated steering

A front loader with articulated steering.

Articulated steering is a system by which a four-wheel drive vehicle is split into front and rear halves which are connected by a vertical hinge. The front and rear halves are connected with one or more hydraulic cylinders that change the angle between the halves, including the front and rear axles and wheels, thus steering the vehicle. This system does not use steering arms, king pins, tie rods, etc. as does four-wheel steering. If the vertical hinge is placed equidistant between the two axles, it also eliminates the need for a central differential, as both front and rear axles will follow the same path, and thus rotate at the same speed.

Rear wheel steering

A few types of vehicle use rear wheel steering, notably fork lift trucks, early pay loaders, Buckminster Fuller's Dymaxion car, and the ThrustSSC.

Rear wheel steering can tend to be unstable because in turns the steering geometry tends to decrease the turn radius (oversteer), rather than increase it (understeer). A rear wheel steered automobile exhibits non-minimum phase behavior. It turns in the direction opposite of how it is initially steered. A rapid steering input will cause two accelerations, first in the direction that the wheel is steered, and then in the opposite direction: a

"reverse response." This makes it harder to steer a rear wheel steered vehicle at high speed than a front wheel steered vehicle.

Steer-by-wire

The aim of *steer-by-wire* technology is to completely do away with as many mechanical components (steering shaft, column, gear reduction mechanism, etc.) as possible. Completely replacing conventional steering system with steer-by-wire holds several advantages, such as:

- The absence of steering column simplifies the car interior design.
- The absence of steering shaft, column and gear reduction mechanism allows much better space utilization in the engine compartment.
- The steering mechanism can be designed and installed as a modular unit.
- Without mechanical connection between the steering wheel and the road wheel, it is less likely that the impact of a frontal crash will force the steering wheel to intrude into the driver's survival space.
- Steering system characteristics can easily and infinitely be adjusted to optimize the steering response and feel.

As of 2007 there are no production cars available that rely solely on steer-by-wire technology due to safety, reliability and economic concerns, but this technology has been demonstrated in numerous concept cars and the similar *fly-by-wire* technology is in use in both military and civilian aviation applications. Removing the mechanical steering linkage in road going vehicles would require new legislation in most countries.

Safety

For safety reasons all modern cars feature a collapsible steering column (energy absorbing steering column) which will collapse in the event of a heavy frontal impact to avoid excessive injuries to the driver. Airbags are also generally fitted as standard. Non-collapsible steering columns fitted to older vehicles very often impaled drivers in frontal crashes, particularly when the steering box or rack was mounted in front of the front axle line, at the front of the crumple zone. This was particularly a problem on vehicles that had a rigid separate chassis frame, with no crumple zone. Most modern vehicle steering boxes/racks are mounted behind the front axle on the front bulkhead, at the rear of the front crumple zone.

Audi used a retractable steering wheel and seat belt tensioning system called procon-ten, but it has since been discontinued in favor of airbags and pyrotechnic seat belt pre-tensioners.

Collapsible steering columns were invented by Bela Barenyi and were introduced in the 1959 Mercedes-Benz W111 Fintail, along with Crumple zones.

This safety feature first appeared on cars built by General Motors after an extensive and very public lobbying campaign enacted by Ralph Nader.

Ford started to install collapsible steering columns in 1968.

Cycles

Steering is crucial to the stability of bicycles and motorcycles.

Ship and boat steering

Ships and boats are usually steered with a rudder. Depending on the size of the vessel, rudders can be manually actuated, or operated using a servomechanism, or a trim tab/servo tab system.

Chapter 5

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.

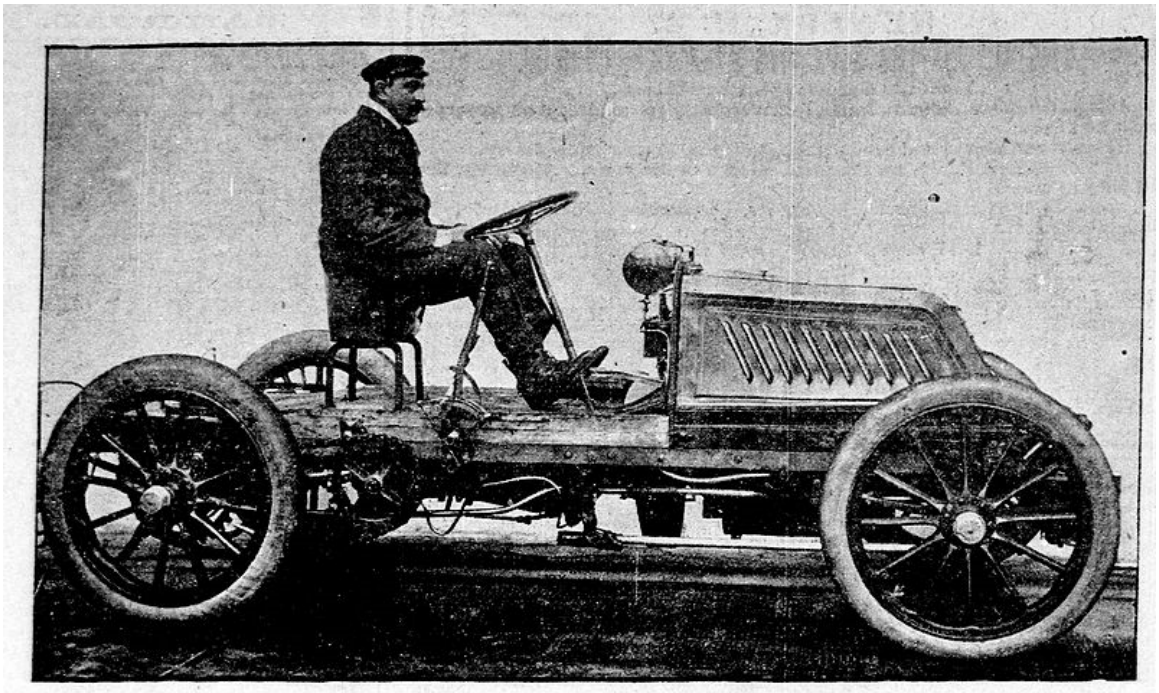
Ancient military engineers used leaf springs in the form of bows to power their siege engines, with little success at first. The use of leaf springs in catapults was later refined and made to work years later. Springs were not only made of metal, a sturdy tree branch could be used as a spring, such as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

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

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~-7° 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

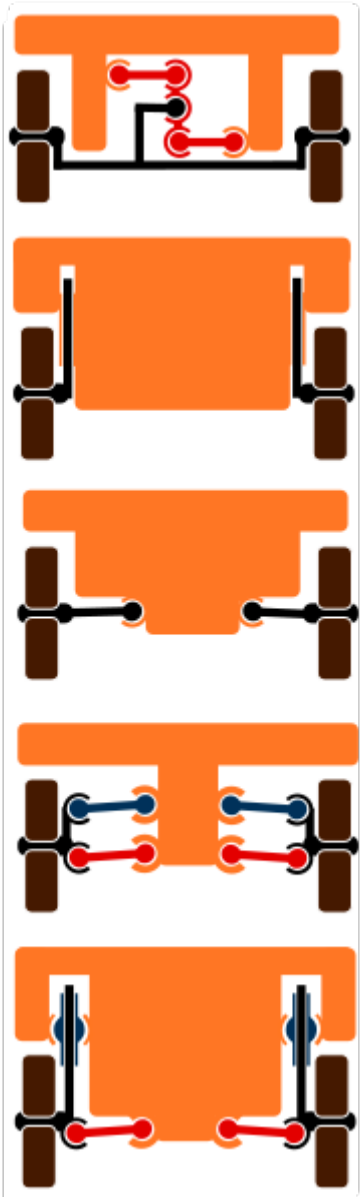
Interconnected suspension, unlike semi-active/active suspensions, could easily decouple different vehicle vibration modes in a passive manner. The interconnections can be realized by various means, such as mechanical, hydraulic and pneumatic. Anti-roll bars are one of the typical examples of mechanical 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.

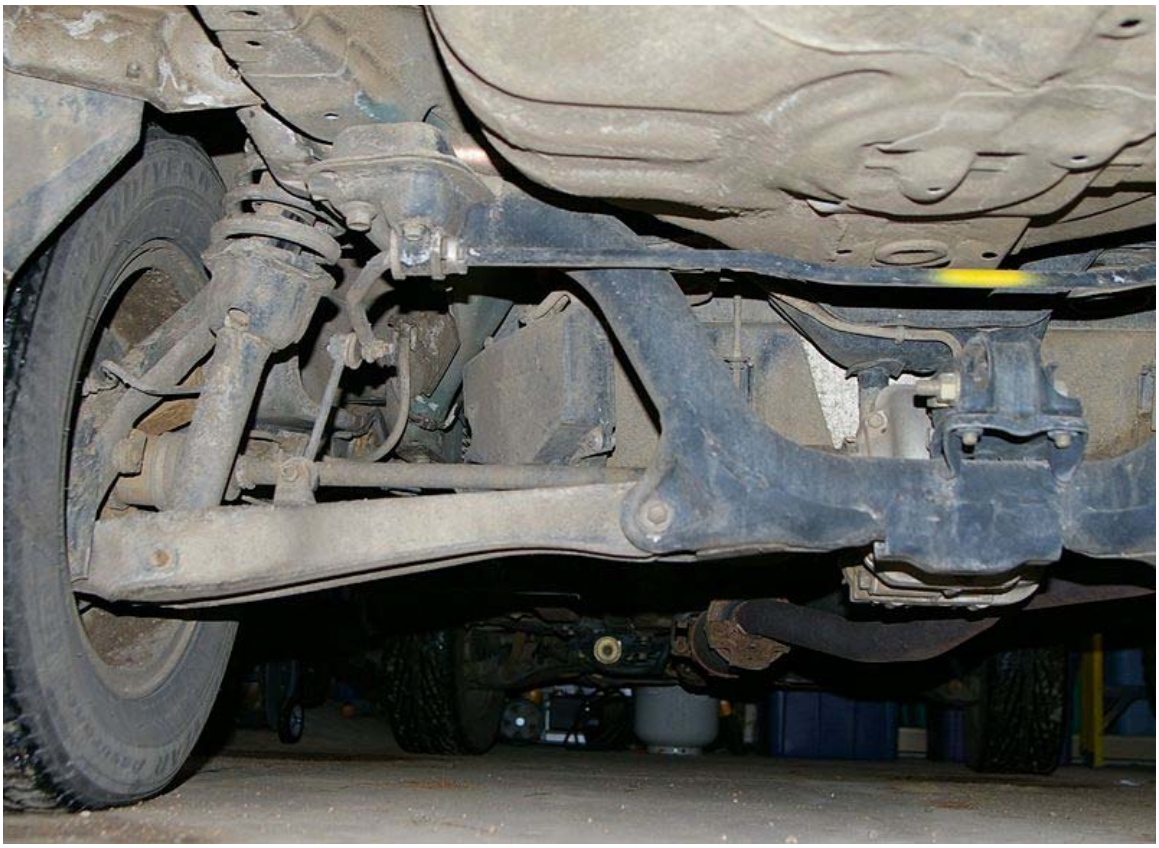
Examples of location linkages include:

- 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 6

Understeer

Understeer and **oversteer** are vehicle dynamics terms used to describe the sensitivity of a vehicle to steering. Automotive engineers originally defined understeer and oversteer based on the gradient of the steering needed to make a turn in a steady-state condition (constant speed, constant radius) on a flat and level ground surface. Car and motorsport enthusiasts often use the terminology more generally in magazines and blogs to describe vehicle response to steering in all kinds of maneuvers, even on banked turns. Simply put, oversteer is what occurs when a car turns(steers) by more than(over) the amount commanded by the driver. Conversely, understeer is what occurs when a car steers under the amount commanded by the driver.

Vehicle Dynamics Terminology

In standard terminology defined by the Society of Automotive Engineers (SAE) J670 and the International Organization for Standardization (ISO) 8855, understeer and oversteer are based on differences in steady-state conditions where the vehicle is following a constant-radius path at a constant speed with a constant steering wheel angle, on a flat and level surface. If the speed is increased slightly for the same radius path and, after settling into steady state, the same steering is measured, then the vehicle is said to have neutral steer. If more steering is needed at the higher speed to maintain the same radius of curvature, then the vehicle is said to have understeer. If less steering is needed at the higher speed, then the vehicle is said to have oversteer.

Understeer and oversteer are defined by an understeer gradient U that is the difference between a reference steer angle gradient and the Ackerman steer angle gradient. The reference steer angle (δ_R) is the average steer of the front axle wheels minus the average steer of the rear axle wheels. The Ackerman steer angle (δ_A) is defined for a given radius of turn as the reference steer angle that would be used at a very low speed. For a four-wheeled vehicle with steering only at the front wheels, the Ackerman angle δ_A (at the wheels) is the arctangent of the wheelbase divided by the turn radius (at the center of the rear axle).

Understeer and oversteer are formally defined using the gradient U: if U is positive, the vehicle is understeer; if U is negative, the vehicle is oversteer; if U is zero, the vehicle is neutral.

Different companies and organizations have different test procedures for defining U. In all cases, the gradient is taken by comparing measures from steady state tests, and expressed with units of degrees of steer (at the road wheels) divided by lateral acceleration Ay expressed in g's. In steady-state conditions, $Ay = V^2/R/G$, where V is the vehicle speed, R is the radius of the turn, and G is the gravitational scaling factor.

SAE J670 describes three methods for measuring U:

1. Constant radius: tests are repeated at different speeds for a given constant-radius track. In this kind of procedure, the Ackerman steering is always the same, so the gradient is: $U = d(\delta_R)/d(Ay)$
2. Constant steer angle: tests are repeated at different speeds for a given reference steer angle. In this kind of procedure, the reference steer is always the same so the gradient is: $U = -d(\delta_A)/d(Ay)$
3. Constant speed: tests are repeated with different reference steer angles for a given speed. In this kind of procedure, the gradient is: $U = d(\delta_R)/d(Ay) - d(\delta_A)/d(Ay)$

Gillespie goes into more detail on applying the first and third measurement methods.

Results depend on the type of test, so just giving a deg/g value is not sufficient; it is also necessary to indicate the type of procedure used to measure the gradient.

Vehicles are inherently nonlinear systems, and it is normal for U to vary over the range of testing. It is possible for a vehicle to be understeer in some conditions and oversteer in others. Therefore, it is necessary to specify the speed and lateral acceleration whenever reporting understeer/oversteer characteristics.

Contributions to understeer

Many properties of the vehicle affect the understeer gradient, including tire cornering stiffness, camber thrust, lateral force compliance steer, aligning torque, lateral load transfer, and compliance in the steering system. These individual contributions can be identified analytically or by measurement in a Bundorf analysis.

Limit conditions

When an understeer vehicle is taken to frictional limits where it is no longer possible to increase lateral acceleration, the vehicle will follow a path with a radius larger than intended. Although the vehicle cannot increase lateral acceleration, it is dynamically stable.

When an oversteer vehicle is taken to frictional limits, it becomes dynamically unstable with a tendency to spin out. Although the vehicle is unstable in open-loop control, a skilled driver can maintain control a little past the point of instability with counter-steering. However, at some limit in lateral acceleration, it is not physically possible for even the most skilled driver to maintain a steady state and spinout will occur.

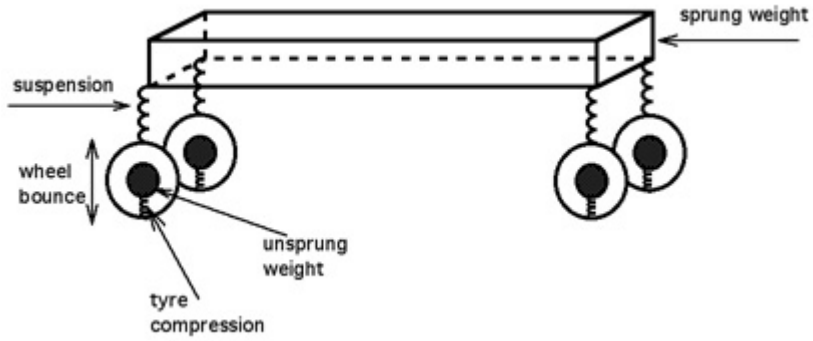
Related measures

Understeer gradient is one of the main measures for characterizing steady-state cornering behavior. It is involved in other properties such as characteristic speed (the speed for an understeer vehicle where the steer angle needed to negotiate a turn is twice the Ackerman angle), lateral acceleration gain (g's/deg), yaw velocity gain (1/s), and critical speed (the speed where an oversteer vehicle has infinite lateral acceleration gain).

Chapter 7

Unsprung Mass and Vehicle Dynamics

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 tire 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.

Vehicle dynamics

Vehicle dynamics refers to the dynamics of vehicles, here assumed to be ground vehicles. Vehicle dynamics is a part of engineering primarily based on classical mechanics but it may also involve chemistry, solid state physics, electrical engineering, communications, psychology, control theory, etc.

Components

Components, attributes or aspects of vehicle dynamics include:

- Electronic Stability Control (ESC)
- Steering
- Suspension
- Traction control system (TCS)

Aerodynamic specific

Some attributes or aspects of vehicle dynamics are purely aerodynamic. These include:

- Automobile drag coefficient
- Automotive aerodynamics
- Center of pressure
- Downforce
- Ground effect in cars

Geometry specific

Some attributes or aspects of vehicle dynamics are purely geometric. These include:

- Ackermann steering geometry
- Axle track
- Camber angle
- Caster angle
- Ride height
- Roll center
- Toe
- Wheelbase

Mass specific

Some attributes or aspects of vehicle dynamics are purely due to mass and its distribution. These include:

- Center of mass
- Moment of inertia
- Sprung mass
- Unsprung mass
- Weight distribution

Motion specific

Some attributes or aspects of vehicle dynamics are purely dynamic. These include:

- Body flex
- Bump Steer
- Directional stability
- Critical speed
- Load transfer
- Noise, vibration, and harshness
- Oversteer
- Ride quality
- Speed wobble
- Understeer
- Weight transfer

Tire specific

Some attributes or aspects of vehicle dynamics can be attributed directly to the tires. These include:

- Camber thrust
- Circle of forces
- Contact patch
- Cornering force
- Ground pressure
- Pacejka's Magic Formula
- Pneumatic trail
- Relaxation length
- Rolling resistance
- Self aligning torque
- Slip angle
- Slip (vehicle dynamics)
- Steering ratio
- Tire load sensitivity

Driving techniques

Driving techniques which relate to, or improve the stability of vehicle dynamics include:

- Cadence braking
- Threshold braking
- Double declutching
- Drifting (motorsport)
- Handbrake turn
- Heel-and-Toe
- Left-foot braking
- Opposite lock
- Scandinavian flick

Analysis and simulation

The dynamic behavior of vehicles can be analysed in several different ways. This can be a straightforward as a simple spring mass system, through a 3 degree of freedom (DoF) bicycle model, to a large degree of complexity using a multibody system simulation package such as MSC ADAMS or Modelica. As computers have gotten faster, and software user interfaces have improved, commercial packages such as CarSim have become widely used in industry for rapidly evaluating hundreds of test conditions much faster than real time. Vehicle models are often simulated with advanced controller designs provided as software in the loop (SIL) with controller design software such as Simulink, or with physical hardware in the loop (HIL).

Vehicle motions are largely due to the shear forces generated between the tires and road, and therefore the tire model is an essential part of the math model. The tire model must produce realistic shear forces during braking, acceleration, cornering, and combinations, on a range of surface conditions. Many models are in use. Most are semi-empirical, such as the Pacejka Magic Formula model.

Racing car games or simulators are also a form of vehicle dynamics simulation. In early versions many simplifications were necessary in order to get real-time performance with reasonable graphics. However, improvements in computer speed have combined with interest in realistic physics, leading to driving simulators that are used for vehicle engineering using detailed models such as CarSim.

It is important that the models should agree with real world test results, hence many of the following tests are correlated against results from instrumented test vehicles.

Techniques include:

- Linear range constant radius understeer
- Fishhook
- Frequency response
- Lane change
- Moose test
- Sinusoidal steering
- Swept path analysis

Chapter 8

Weight Transfer

A motorcyclist performing a stoppie.

Camaro performing a wheelie during drag racing

A Toyota MR2 leaning to the outside of a turn.

Weight transfer and **load transfer** are two expressions used somewhat confusingly to describe two distinct effects: the change in load borne by different wheels of even perfectly rigid vehicles during acceleration, and the change in center of mass (CoM) location relative to the wheels because of suspension complience or cargo shifting or sloshing. In the automobile industry, **weight transfer** customarily refers to the change in load borne by different wheels during acceleration. This is more properly referred to as **load transfer**, and that is the expression used in the motorcycle industry, while **weight transfer** on motorcycles, to a lesser extent on automobiles, and cargo movement on either is due to a change in the CoM location relative to the wheels.

Load transfer

In wheeled vehicles, **load transfer** is the measurable change of load borne by different wheels during acceleration (both longitudinal and lateral). This includes braking, and deceleration (which is an acceleration at a negative rate). No motion of the centre of gravity (CoG) relative to the wheels is necessary, and so load transfer may be experienced by vehicles with no suspension at all. Load transfer is a crucial concept in understanding vehicle dynamics. The same is true in bikes, though only longitudinally.

Cause

The major forces that accelerate a vehicle occur at the tires' contact patches. Since these forces are not directed through the vehicle's CoG, one or more moments are generated whose forces are the tyres traction forces at pavement level, the other one (equal but opposed) is the mass inertia located at (CoG) and the arm is the distance from pavement surface to CoG. It is these moments that cause variation in the load distributed between the tires. Often this is interpreted by the casual observer as a pitching or rolling motion of the vehicles body. A perfectly rigid vehicle without suspension that would not exhibit pitching or rolling of the body still undergoes load transfer. However, the pitching and rolling of the body adds some (small) weight transfer due to the (small) CoG horizontal displacement with respect to the wheels axis suspension vertical travel and also due to deformation of the tires i.e. contact patch displacement relative to wheel.

Lowering the CoG towards the ground is one method of reducing load transfer. As a result load transfer is reduced in both the longitudinal and lateral directions. Another method of reducing load transfer is by increasing the wheel spacings. Increasing the vehicle's wheel base (length) reduces longitudinal load transfer while increasing the vehicle's track (width) reduces lateral load transfer. Most high performance automobiles are designed to sit as low as possible and usually have an extended wheel base and track.

Weight transfer

Weight transfer involves the *actual* (relatively small) movement of the vehicle CoG relative to the wheel axes due to displacement of the chassis as the suspension complies, or of cargo or liquids within the vehicle, which results in a redistribution of the total vehicle load between the individual tires.

Center of gravity

Weight transfer occurs as the vehicle's center of gravity (CoG) shifts during automotive maneuvers. Acceleration causes the sprung mass to rotate about a geometric axis resulting in relocation of the CoG. Front-back weight transfer is proportional to the change in the longitudinal location of the center of gravity to the vehicle's wheelbase, and side-to-side weight transfer (summed over front and rear) is proportional to the ratio of the change in the center of gravity's lateral location to the vehicle's track.

Liquids, such as fuel, readily flow within their containers, causing changes in the vehicle's CoG. As fuel is consumed, not only does the position of the CoG change, but the total weight of the vehicle is also reduced.

By way of example, when a vehicle accelerates, a weight transfer toward the rear wheels can occur. An outside observer might witness this as the vehicle visibly leans to the back, or squats. Conversely, under braking, weight transfer toward the front of the car can occur. Under hard braking it might be clearly visible even from inside the vehicle as the nose dives toward the ground (most of this will be due to load transfer). Similarly, during changes in direction (lateral acceleration), weight transfer to the outside of the direction of the turn can occur.

Weight transfer is generally of far less practical importance than load transfer, for cars and SUVs at least. For instance in a 0.9g turn, a car with a track of 1650 mm and a CG height of 550 mm will see a load transfer of 30% of the vehicle weight, that is the outer wheels will see 30% more load than before, and the inners 30% less. Total available grip will drop by around 3% as a result of this load transfer. At the same time, the CG of the vehicle will typically move laterally and vertically, relative to the contact patch by no more than 30 mm, leading to a weight transfer of less than 2%, and a corresponding reduction in grip of 0.01%.

Traction

Load transfer causes the available traction (engineering) at all four wheels to vary as the car brakes, accelerates, or turns. This bias to one pair of tires doing more `work' than the other pair results in a net loss of total available traction. The net loss can be attributed to the phenomenon known as tire load sensitivity.

An exception is during positive acceleration when the engine power is driving two or fewer wheels. In this situation where all the tires are not being utilized load transfer can be advantageous. As such, the most powerful cars are almost never front wheel drive, as the acceleration itself causes the front wheels' traction to decrease. This is why sports cars usually have either rear wheel drive or all wheel drive (and in the all wheel drive case, the power tends to be biased toward the rear wheels under normal conditions).

Rollover

If (lateral) load transfer reaches the tire loading on one end of a vehicle, the inside wheel on that end will lift, causing a change in handling characteristic. If it reaches half the weight of the vehicle it will start to roll over. Some large trucks will roll over before skidding, while passenger vehicles and small trucks usually roll over only when they leave the road. Fitting racing tires to a tall or narrow vehicle and then driving it hard may lead to rollover.

Chapter 9

Drifting (Motorsport)

A Toyota Supra in drifting exhibition in Commerce, Georgia in 2005.

Drifting refers to a driving technique and to a motorsport where the driver intentionally over steers, causing loss of traction in the rear wheels through turns, while maintaining vehicle control and a high exit speed. A car is drifting when the rear slip angle is greater than the front slip angle prior to the corner apex, and the front wheels are pointing in the opposite direction to the turn (e.g. car is turning left, wheels are pointed right or vice

versa), and the driver is controlling these factors. As a motor sport, professional drifting competitions are held worldwide. Drift racing challenges drivers to navigate a course in a sustained sideslip by exploiting coupled nonlinearities in the tire force response.

History

Japanese Origin

Modern drifting as a sport started out as a racing technique popular in the All Japan Touring Car Championship races. Motorcycling legend turned driver, Kunimitsu Takahashi, was the foremost creator of drifting techniques in the 1970s. He is noted for hitting the apex (the point where the car is closest to the inside of a turn) at high speed and then drifting through the corner, preserving a high exit speed. This earned him several championships and a legion of fans who enjoyed the spectacle of smoking tires. The bias ply racing tires of the 1960s-1980s lent themselves to driving styles with a high slip angle. As professional racers in Japan drove this way, so did the street racers.

Keiichi Tsuchiya (known as the Dorikin/Drift King) became particularly interested by Takahashi's drift techniques. Tsuchiya began practicing his drifting skills on the mountain roads of Japan, and quickly gained a reputation amongst the racing crowd. In 1987, several popular car magazines and tuning garages agreed to produce a video of Tsuchiya's drifting skills. The video, known as Pluspy, became a hit and inspired many of the professional drifting drivers on the circuits today. In 1988, alongside *Option magazine* founder and chief editor Daijiro Inada, he would help to organize one of the first events specifically for drifting called the D1 Grand Prix. He also drifted every turn in Tsukuba Circuit in Japan.

Western Adoption

One of the earliest recorded drift events outside Japan was in 1996, held at Willow Springs Raceway in Willow Springs, California hosted by the Japanese drifting magazine and organization Option. Inada, founder of the D1 Grand Prix in Japan, the NHRA Funny Car drag racer Kenji Okazaki and Keiichi Tsuchiya, who also gave demonstrations in a Nissan 180SX that the magazine brought over from Japan, judged the event with Rhys Millen and Bryan Norris being two of the entrants. Drifting has since exploded into a massively popular form of motorsport in North America, Australasia, and Europe.

Present Day

Drifting has evolved into a competitive sport where drivers compete mostly in rear wheel drive cars, and occasionally all wheel drive cars, to earn points from judges based on various factors. At the top levels of competition, the D1 Grand Prix in Japan pioneered the sport. Others such as Pro-drift in Europe, Formula D in the United States, and the NZ Drift Series in New Zealand have come along to further expand it into a legitimate motor sport worldwide. The drivers within these series were originally influenced by the

pioneers from D1 Japan and are able to keep their cars sliding for extended periods of time, often linking several turns.

Amateur "Tafheet" or "Hjwalah" drifting on public roads is a significant problem in Saudi Arabia.

Drift competition

Drifting competitions are judged based on line, angle, speed, and show factor. Line involves taking the correct line, which is usually announced beforehand by judges. The show factor is based on multiple things, such as the amount of smoke, how close the car is to the wall or designated clipping point, and the crowd's reaction. Angle is the angle of a car in a drift, speed is the speed entering a turn, the speed through a turn, and the speed exiting the turn; faster is better.

Team Drift Competition in Melbourne.

The judging takes place on just a small part of the circuit, a few linking corners that provide good viewing, and opportunities for drifting. The rest of the circuit is irrelevant, except as it pertains to controlling the temperature of the tires and setting the car up for the first judged corner. In the tandem passes, the lead driver often feints his or her entry to the first corner to upset the chase driver.

There are typically two sessions, a qualifying/practice session, and a final session. In the qualifying sessions, referred as **Tansou** *(単走:speed run)*, drifters get individual passes in front of judges (who may or may not be the final judges) to try and make the final 16. This is often on the day preceding the final.

The finals are tandem passes, referred as **Tsuiso** *(追走:chase attack)*. Drivers are paired off, and each heat comprises two passes, with each driver taking a turn to lead. The best

of the 8 heats go to the next 4, to the next 2, to the final. The passes are judged as explained above, however there are some provisos such as:

- Overtaking the lead car under drift conditions almost always wins that pass.
- Overtaking the lead car under grip conditions automatically forfeits that pass.
- Spinning forfeits that pass, unless the other driver also spins.
- Increasing the lead under drift conditions helps to win that pass.
- Maintaining a close gap while chasing under drift conditions helps to win that pass.

Points are awarded for each pass, and usually one driver prevails. Sometimes the judges cannot agree, or cannot decide, or a crowd vocally disagrees with the judge's decision. In such cases more passes may be run until a winner is produced. Sometimes mechanical failure determines the battle's outcome, either during or preceding a heat. If a car cannot enter a tandem battle, the remaining entrant (who automatically advances) will give a solo demonstration pass. In the event of apparently close or tied runs, crowds often demonstrate their desire for another run with chants of 'one more time'.

There is some regional variation. For example in Australia, the chase car is judged on how accurately it emulates the drift of the lead car, as opposed to being judged on its own merit, this is only taken into consideration by the judges if the lead car is on the appropriate racing line. Other variations of the tansou/tsuiso and the tansou only method is the multi-car group judging, seen in the Drift Tengoku videos where the four car team is judged in groups.

Cars

Usually, drift cars are light to moderate weight rear-wheel-drive coupes and sedans over a large range of power levels. In Japan and worldwide, the most common drift vehicles are the Nissan Silvia/180SX/200SX/240SX, Toyota AE86, Toyota KE70, Mazda RX-7, Mazda RX-8, Infiniti G35 Coupe, Nissan A31 Cefiro, Nissan C33 Laurel, Nissan Skyline (AWD versions, such as the GT-R, are often converted to RWD), Nissan 350Z, Toyota Altezza/Lexus IS, Toyota Chaser, Toyota Mark II, Toyota Soarer, Honda S2000, Toyota Supra, Dodge Viper SRT 10, Ford Mustang and Mazda Miata/MX-5.

There have also been AWD rally cars that have been converted to RWD, such as the Mitsubishi Lancer Evolution and Subaru Impreza WRX STi.

Drifting Toyota AE86

Despite the export of Japanese Domestic Market (JDM) vehicles to continents outside Japan, it is notable that drifters within other countries prefer to use local examples as drift cars.

A high volume of JDM imports were brought to countries such as Australia, however it is not unusual to see Australian domestic vehicles such as the Holden Commodore or Ford Falcon utilised in drifting competitions.

Drifters in other countries often use local favorites, such as the Vauxhall Omega in the UK and Ireland, BMW 3 Series, BMW M3, Ford Sierra, Volvo 240, Volvo 340 (other parts of Europe), Mercedes-Benz cars, Porsche cars, and Alfa Romeo 75.

The American market enjoyed a relatively high volume of JDM cars being imported over the last decade, despite Japanese domestic vehicles being right-hand-drive only. Locally-sold imports such as the Lexus SC and Nissan 240SX feature heavily in American drifting, however they are usually modified with JDM engine transplants to mirror their Japanese domestic equivalents (usually with a Toyota 1JZ-GTE/2JZ-GTE or Nissan CA18DET/SR20DET respectively).

As an example, the top 15 cars in the 2003 D1GP, top 10 in the 2004 D1GP, and top 10 in the 2005 D1GP were:

Nissan Silvia S15 drifting

Car	Model	2003	2004	2005
Nissan Silvia	S15	6 cars	5 cars	3 cars
Toyota Levin/Trueno	AE86	3 cars	3 cars	2 cars
Mazda RX-7	FD3S	2 cars	1 car	2 cars
Nissan Skyline	R34	1 car	1 car	1 car
Nissan Silvia	S13	2 cars		
Toyota Chaser	JZX100	1 car		
Subaru Impreza	GD (RWD)			1 car
Toyota Altezza	SXE10			1 car

The Top cars in the Red Bull Drifting Championship:

Driver	Make	Model
Vaughn Gittin JR.	Ford	Mustang
Tanner Foust	Scion	tC
Justin Pawlak	Mazda	RX7

Issac Yakuza	Infiniti	Q45
Hiro Sumida	Lexus	IS350
Casper Canul	Nissan	240SX
Ken Gushi	Nissan	Silvia 240sx S13
Kevin Huynh	Mopar	Viper SRT10
Dai Yoshihara	Lexus	IS350
Calvin Wan	Infiniti	G35
Rhys Millen	Hyundai	Genesis Coupe V6
Vanessa Ozawa	Dodge	Magnum SRT8
Robbie Nishida	Nissan	350Z
Sam Hubinette	Dodge	Charger
Chris Forsberg	Nissan	350Z
Ross Petty	Hyundai	Genesis
Michael Essa	BMW	350R M V10
Nathan Jones	BMW	M3

FWD cars do qualify for entrance into some drifting events, but are rarely used due to the lack of parity between FWD and RWD cars. AWD vehicles, such as the Nissan Skyline GTR, Subaru Impreza WRX STi, and Mitsubishi Lancer Evolution can drift but usually need to be converted to RWD. In D1 Grand Prix, these cars are modified to RWD specification.

Drift tuning

Drive train

A proper mechanical limited slip differential (LSD) is almost considered essential for drifting. Attempting to drift with an open or viscous differential in a sustained slide generally yields relatively less impressive results. All other modifications are secondary to the LSD. Two popular LSD brands amongst drifters are OS Giken & Cusco.

The most preferred form of LSD for drifting is the clutch type, in "2-way" form, for its consistent and aggressive lockup behavior under all conditions (acceleration and deceleration). Some drift cars use a spool "differential", which actually has no differential action at all - the wheels are locked to each other. Budget-minded drifters may use a welded differential, where the side gears are welded to give the same effect as a spool. This makes it easier to break rear traction because it reduces maximum traction in all situations except traveling in a straight line. Welded differentials have an inherent risk involved, due to the tremendous amounts of internal stress the welds may fail and the differential completely locks up leaving the rear wheels immobilized. Helical torque sensing types such as the Torsen or Quaife (available on cars in certain stock trims such as S15, FD3S, MX-5, JZA8x, UZZ3x) differentials are also adequate.

The clutches on drift cars tend to be very tough ceramic brass button or multiple-plate varieties, for durability, as well as to allow rapid "clutch kick" techniques to upset the balance of the car. Gearbox and engine mounts are often replaced with urethane or aluminum mounts, and dampers added to control the violent motion of the engine/gearbox under these conditions.

Gearsets may be replaced with closer ratios to keep the engine in the power band. These may be coarser dog engagement straight cut gears instead of synchronised helical gears, for durability and faster shifting at the expense of noise and refinement. Wealthier drifters may use sequential gearboxes to make gear selection easier/faster, while sequential shift lever adapters can be used to make shifts easier without increasing shift time.

Suspension

The suspension in a drift car tends to have very high spring and damper rates. Sway bars are upgraded, particularly on the rear. Caster is often increased to improve the car's controllability during a slide. Most cars use an integrated coilover/shock (MacPherson strut) combination. This type of suspension allows the ride height to be adjusted independently of the suspension travel. There is no perfect height setting or spring/shock combo for any car, but each driver will have their own personal preference. Many suspension manufacturers offer suspension tuned specifically for drifting. Bushings can be upgraded with urethane parts.

Positive camber is never desired. There is such a thing as too much negative camber. Making the wheel/tire go into static negative camber on a vehicle with a MacPherson strut front suspension counteracts the positive camber change. However, there is a level at which you over-counteract and thus the tire is always in a negative-camber situation. This is not wanted because it will both wear the tires prematurely and decrease contact patch and thus decreasing overall grip. In the rear, less negative camber (if any) is often used and, if it is used, it is usually to tweak the balance of the car. The old-school Japanese drifters used to run oni-kyan ("demon camber") so they could get their tires to spin easily even though they had very little power. It has thus fallen out of favor as a serious performance-minded suspension setup. However, many cars built for show (such as those driven by bōsōzoku) still use this style of suspension setup for its aggressive look. A few degrees of toe-out on the rear wheels (leading edges angled outward) can reduce rear stability, and make setting up a drift easier.

Cockpit

Because of the large centripetal force encountered during drifting, drivers find it preferable to be retained firmly by a bucket seat, and harness. This allows the hands to merely turn the wheel, as opposed to bracing oneself against the wheel. The steering wheel should be relatively small, dished, and perfectly round, so that it can be released and allowed to spin through the hands as the caster returns the front wheels to center. The locking knob on the hand brake is usually replaced with a spin turn knob, this stops the hand brake locking on when pulled. Some drivers move the hand brake location or add an

extra hydraulic hand brake actuator for greater braking force. Many drivers make use of additional gauges to monitor such things as boost levels, oil, intake and coolant temperatures.

Engine

S13 Silvia bay with modifications for drifting.

Engine power does not need to be high, and in fact if a car has too much power, it can be very hard to handle during a drift. Each driver has their own preference, and drift cars can be found with anything from 100 bhp (74 kW) to 1000 bhp (745 kW). Typically, engine tuning is oriented towards achieving linear response rather than maximum power output. Engines also must be equipped with upgraded cooling systems. Not only are the engines pushed very hard, creating lots of heat, but being driven at an angle reduces the airflow through the radiator. For turbocharged engines, intercooler efficiency is similarly reduced. Oil coolers are almost essential. V-mounting the intercooler and radiator improves flow through these components, and keeps the expensive intercooler out of harm's way in the case of a minor accident.

Steering

With increased steering angle it is possible to achieve greater angle with the vehicle, also aiding in spin recovery. This is often done with spacers on the steering rack, custom

steering racks, custom tierod ends, or machining the spindles. In extreme cases increasing the steering angle may come to a point where the tire or wheel comes into contact with other suspension pieces or the inner/outer fenders; in which case additional modifications are required if such contacts are to be avoided.

Body

Cleaning up severed bumpers during drift meet.

Chassis preparation is similar to a road racing car. Roll cages are sometimes employed for safety, and to improve the torsional rigidity of the car's frame, but are compulsory in events that involves the 2+ cars' tsuiso runs in the event of a side collision. Front and rear strut tower braces, B-pillar braces, lower arm braces, and master cylinder braces are all used to stiffen the chassis. The interior is stripped of extraneous seating, trim, carpet, sound deadening; anything that is not essential is removed to reduce weight.

Body kits are often attached with cable ties. When the body kit meets the wall or curb, the cable ties snap, releasing the part, as opposed to breaking it.

As drift cars are pushed faster, aerodynamic tuning becomes more important as well. Rear spoilers and wings usually are useful only in large, open tracks where the cars develop enough speed to create a need for more downforce. Wheel arches are often rolled or flared to allow the fitment of larger tires. Airflow to the engine is critical, so the hood is often vented.

Due to the nature of the hobby, drift cars are typically involved in many minor accidents.

Tires

S13 Silvia - tire stretched over a wide rim, increasing sidewall rigidity. The rim has a low offset to increase track.

The cars quite often have different tires on the front and back, and the owner may have quite a few sets. As a rule, good tires go on the front for good steering. On the back, hard-compound tires are used, quite often second-hand ones tend to end up in a cloud of smoke. 15" wheels are common on the rear, as 15" tires are cheap. As a driver gets better, they will most likely want to upgrade the tires used in the rear for a higher grip compound. Although cheap/hard tires are fun purely for their slipperiness and ease of drifting, they quickly become a hazard for high-speed drifts. More advanced drivers require the most grip possible from all 4 tires, so as to retain control adequately during high speed drifts. Competitive drifters often run DOT-approved tires closer to racing

tires, which is permitted, with the exception of some major championships including D1GP which only permits commercially available tires that are approved by them. The grip is required for control, speed, and a fast snap on the initial entry. Generally drifting consumes tires rapidly and multiple sets may be necessary for a single event.

Some companies, such as Kumho Tires, created tires with special effects for drifting. These tires produce colored smoke instead of regular grey smoke when drifted. Lavender-scented tires have also been developed. They are not permitted in many competitions, as they are seen as giving an unfair advantage to teams with the funding to use them.

R/C drifting

R/C drifting refers to the act of drifting with a radio-controlled car. R/C cars are equipped with special low grip tires, usually made from PVC or ABS piping. Some manufacturers make radial drift tires that are made of actual rubber compounds. The car setup is usually changed to allow the car to drift more easily. R/C drifting is most successful on 4WD (Four wheel drive) R/C cars. Companies such as Tamiya, Yokomo, Team Associated, and Hobby Products International have made drift cars and supported the hobby.

Drifting in the Media

Film

One of the key sources responsible for the international spread of drifting is the Japanese anime series Initial D, which features Takumi, a school boy who learns to drift on the Mt. Akina touge (mountain pass) when delivering tofu for his father's business. Hollywood embraced the drifting subculture in the The Fast and the Furious: Tokyo Drift, which is based solely on drifting.

Computer/Console Gaming

Drifting's popularity in computer games extends back to early arcade racers where the techniques for games such as Sega Rally and Ridge Racer involved drifting. The technique is now considered mainstream in modern games in all their forms. In-game communities have developed in games such as Forza Motorsport and Gran Turismo, made up of teams who battle in user-created tournaments.

Drifting also features heavily in the Need for Speed Franchise (notably games since Need for Speed: Underground), the Juiced franchise and in Japanese domestic console games such as Initial D: Extreme Stage (PS3), which is based solely on drifting.

Browser-based games include NZ Performance Car's Drift Legends (the first online game to feature real racetracks, and now ported to iPhone/iPod touch), and Mercedes-

AMG's Wintersport Drift Competition (the first manufacturer-backed drifting game). Drifting games for mobile devices are readily available from major manufacturers.

Corporate support behind such games demonstrates the increased value advertisers are putting on drifting's reach into key demographics.

Documentaries

High Performance Imports. Volume 10, features Australian journalists from express publications, and Australian professional drifter Darren Appleton travelling to Japan, purchasing a drift vehicle (Nissan R32 GTS-T 4-door), travelling with the likes of D1 champions and entering a drift event.

Chapter 10

Electronic Stability Control

Electronic stability control (**ESC**) is a computerized technology that improves safety of a vehicle's stability by detecting and minimizing skids. When ESC detects loss of steering control, it automatically applies the brakes to help "steer" the vehicle where the driver intends to go. Braking is automatically applied to wheels individually, such as the outer front wheel to counter oversteer or the inner rear wheel to counter understeer. Some ESC systems also reduce engine power until control is regained. ESC does not improve a vehicle's cornering performance; instead, it helps to minimize the loss of control. According to IIHS and NHTSA, one-third of fatal accidents could have been prevented by the technology.

History

In 1987, the earliest innovators of ESC, Mercedes-Benz and BMW, introduced their first traction control systems. Traction control works by applying individual wheel braking and throttle to keep traction while accelerating but, unlike the ESC, it is not designed to aid in steering.

Named simply TCL in 1990, the system has since evolved into Mitsubishi's modern *Active Skid and Traction Control* (ASTC) system. Developed to help the driver maintain the intended path through a corner, an onboard computer monitored several vehicle operating parameters through the use of various sensors. When too much throttle has been used, while taking a curve, engine output and braking are automatically regulated to ensure the proper path through a curve and to provide the proper amount of traction under various road surface conditions. While conventional traction control systems at the time featured only a slip control function, Mitsubishi developed a TCL system which had a preventive (active) safety feature. This improved the course tracing performance by automatically adjusting the traction force, thereby restraining the development of excessive lateral acceleration, while turning. Although not a ‘true’ modern stability control system, trace control monitors steering angle, throttle position and individual wheel speeds and there is no yaw rate input. The TCL system's standard wheel slip control function improves traction on slippery surfaces or during cornering. In addition to the TCL's traction control feature, it also works together with Diamante's electronic

controlled suspension and four-wheel steering that Mitsubishi had equipped to improve total handling and performance.

BMW, working with Robert Bosch GmbH and Continental Automotive Systems, developed a system to reduce engine torque to prevent loss of control and applied it to the entire BMW model line for 1992. From 1987 to 1992, Mercedes-Benz and Robert Bosch GmbH co-developed a system called Elektronisches Stabilitätsprogramm (Ger. "Electronic Stability Programme" trademarked as ESP) a lateral slippage control system, the electronic stability control (ESC).

GM worked with Delphi Corporation and introduced its version of ESC called "StabiliTrak" in 1997 for select Cadillac models. StabiliTrak was made standard equipment on all GM SUVs and vans sold in the U.S. and Canada by 2007 except for certain commercial and fleet vehicles. While the "StabiliTrak" name is used on most General Motors vehicles for the U.S. market, the "Electronic Stability Control" identity is used for GM overseas brands, such as Opel, Holden and Saab, except in the case of Saab's 9-7X which also uses the "StabiliTrak" name. Ford's version of ESC, called AdvanceTrac, was launched in the year 2000. Ford later added Roll Stability Control to AdvanceTrac which was first introduced in Volvo XC90 in 2003 when Volvo Cars was fully owned by Ford and it is now being implemented in many Ford vehicles.

Introduction

In 1995, automobile manufacturers introduced ESC systems. Mercedes-Benz, supplied by Bosch, was the first to implement this with their W140 S-Class model. That same year BMW, supplied by Bosch and ITT Automotive (later acquired by Continental Automotive Systems). Volvo Cars began to offer their version of ESC called DSTC in 1998 on the new S80. Toyota's Vehicle Stability Control system (also in 2004, a preventive system called VDIM) appeared on the Crown Majesta in 1995. Meanwhile others investigated and developed their own systems.

During a moose test (swerving to avoid an obstacle) which became famous in Germany as "the Elk test" the Swedish journalist Robert Collin of Teknikens Värld (World of Technology) in October 1997 rolled a Mercedes A-Class (without ESC) at 78 km/h. Because Mercedes-Benz promotes a reputation for safety, they recalled and retrofitted 130,000 A-Class cars with ESC. This produced a significant reduction in crashes and the number of vehicles with ESC rose. Today virtually all premium brands have made ESC standard on all vehicles, and the number of models with ESC continues to increase. Ford and Toyota announced that all their North American vehicles would be equipped with ESC standard by the end of 2009 (it was standard on Toyota SUVs as of 2004, and after the 2011 model-year, All Lexus, Toyota, and Scion vehicles have ESC; the last one to get it was the 2011 model-year Scion tC). However, as recent as November 2010, Ford still sells models in North America without ESC. General Motors had made a similar announcement for the end of 2010. The NHTSA requires all passenger vehicles to be equipped with ESC by 2012 and estimates it will prevent 5,300-9,600 annual fatalities once all passenger vehicles are equipped with the system.

Operation

During normal driving, ESC works in the background and continuously monitors steering and vehicle direction. It compares the driver's intended direction (determined through the measured steering wheel angle) to the vehicle's actual direction (determined through measured lateral acceleration, vehicle rotation (yaw), and individual road wheel speeds).

ESC intervenes only when it detects loss of steering control, i.e. when the vehicle is not going where the driver is steering. This may happen, for example, when skidding during emergency evasive swerves, understeer or oversteer during poorly judged turns on slippery roads, or hydroplaning. ESC estimates the direction of the skid, and then applies the brakes to individual wheels asymmetrically in order to create torque about the vehicle's vertical axis, opposing the skid and bringing the vehicle back in line with the driver's commanded direction. Additionally, the system may reduce engine power or operate the transmission to slow the vehicle down.

ESC can work on any surface, from dry pavement to frozen lakes. It reacts to and corrects skidding much faster and more effectively than the typical human driver, often before the driver is even aware of any imminent loss of control. In fact, this led to some concern that ESC could allow drivers to become overconfident in their vehicle's handling and/or their own driving skills. For this reason, ESC systems typically inform the driver when they intervene, so that the driver knows that the vehicle's handling limits have been approached. Most activate a dashboard indicator light and/or alert tone; some intentionally allow the vehicle's corrected course to deviate very slightly from the driver-commanded direction, even if it is possible to more precisely match it.

Indeed, all ESC manufacturers emphasize that the system is not a performance enhancement nor a replacement for safe driving practices, but rather a safety technology to assist the driver in recovering from dangerous situations. ESC does not increase traction, so it does not enable faster cornering (although it can facilitate better-controlled cornering). More generally, ESC works within inherent limits of the vehicle's handling and available traction between the tires and road. A reckless maneuver can still exceed these limits, resulting in loss of control. For example, in a severe hydroplaning scenario, the wheels that ESC would use to correct a skid may not even initially be in contact with the road, reducing its effectiveness.

In July 2004, on the Crown Majesta, Toyota offered a Vehicle Dynamics Integrated Management (VDIM) system that incorporated formerly independent systems, including ESC. This worked not only after the skid was detected but also to prevent the skid from occurring in the first place. Using electric variable gear ratio steering power steering this more advanced system could also alter steering gear ratios and steering torque levels to assist the driver in evasive maneuvers.

Effectiveness

Numerous studies around the world confirm that ESC is highly effective in helping the driver maintain control of the car, thereby saving lives and reducing the severity of crashes. In the fall of 2004 in the U.S., the National Highway and Traffic Safety Administration confirmed the international studies, releasing results of a field study in the U.S. of ESC effectiveness. The NHTSA in United States concluded that ESC reduces crashes by 35%. Additionally, Sport utility vehicles (SUVs) with stability control are involved in 67% fewer accidents than SUVs without the system. The United States Insurance Institute for Highway Safety (IIHS) issued its own study in June 2006 showing that up to 10,000 fatal US crashes could be avoided annually if all vehicles were equipped with ESC The IIHS study concluded that ESC reduces the likelihood of all fatal crashes by 43%, fatal single-vehicle crashes by 56%, and fatal single-vehicle rollovers by 77-80%.

ESC is described as the most important advance in auto safety by many experts. including Nicole Nason, Administrator of the NHTSA, Jim Guest and David Champion of Consumers Union of the Fédération Internationale de l'Automobile (FIA), E-Safety Aware, Csaba Csere, editor of Car and Driver, and Jim Gill, long time ESC proponent of Continental Automotive Systems The European New Car Assessment Program (EuroNCAP) "strongly recommends" that people buy cars fitted with stability control.

The IIHS requires that a vehicle must have ESC as an available option in order for it to qualify for their *Top Safety Pick* award for occupant protection and accident avoidance.

Components and design

ESC incorporates yaw rate control into the anti-lock braking system (ABS). Yaw is a rotation around the vertical axis; i.e. spinning left or right. Anti-lock brakes enable ESC to brake individual wheels. Many ESC systems also incorporate a traction control system (TCS or ASR), which senses drive-wheel slip under acceleration and individually brakes the slipping wheel or wheels and/or reduces excess engine power until control is regained. However, ESC achieves a different purpose than ABS or Traction Control.

The ESC system uses several sensors to determine what the driver wants (input). Other sensors indicate the actual state of the vehicle (response). The control algorithm compares driver input to vehicle response and decides, when necessary, to apply brakes and/or reduce throttle by the amounts calculated through the state space (set of equations used to model the dynamics of the vehicle). The ESC controller can also receive data from and issue commands to other controllers on the vehicle such as an all wheel drive system or an active suspension system to improve vehicle stability and controllability.

The sensors used for ESC have to send data at all times in order to detect possible defects as soon as possible. They have to be resistant to possible forms of interference (rain, holes in the road, etc.). The most important sensors are:

- Steering wheel angle sensor: determines the driver's intended rotation; i.e. where the driver wants to steer. This kind of sensor is often based on AMR-elements.
- Yaw rate sensor : measures the rotation rate of the car; i.e. how much the car is actually turning. The data from the yaw sensor is compared with the data from the steering wheel angle sensor to determine regulating action.
- Lateral acceleration sensor: often based on the Hall effect. Measures the lateral acceleration of the vehicle.
- Wheel speed sensor : measures the wheel speed.

Other sensors can include:

- Longitudinal acceleration sensor: similar to the lateral acceleration sensor in design but can offer additional information about road pitch and also provide another source of vehicle acceleration and speed.
- Roll rate sensor: similar to the yaw rate sensor in design but improves the fidelity of the controller's vehicle model and correct for errors when estimating vehicle behavior from the other sensors alone.

ESC uses a hydraulic modulator to assure that each wheel receives the correct brake force. A similar modulator is used in ABS. ABS needs to reduce pressure during braking, only. ESC additionally needs to increase pressure in certain situations and an active vacuum brake booster unit may be utilized in addition to the hydraulic pump to meet these demanding pressure gradients.

The brain of the ESC system is the Electronic Control Unit (ECU). The various control techniques are embedded in it. Often, the same ECU is used for diverse systems at the same time (ABS, Traction control system, climate control, etc.). The input signals are sent through the input-circuit to the digital controller. The desired vehicle state is determined based upon the steering wheel angle, its gradient and the wheel speed. Simultaneously, the yaw sensor measures the actual state. The controller computes the needed brake or acceleration force for each wheel and directs via the driver circuits the valves of the hydraulic modulator. Via a CAN interface the ECU is connected with other systems (ABS, etc.) in order to avoid giving contradictory commands.

Many ESC systems have an "off" override switch so the driver can disable ESC, which may be desirable when badly stuck in mud or snow, or driving on a beach, or if using a smaller-sized spare tire which would interfere with the sensors. Some systems also offer an additional mode with raised thresholds so that a driver can utilize the limits of adhesion with less electronic intervention. However, ESC defaults to "On" when the ignition is re-started. Some ESC systems that lack an "off switch", such as on many recent Toyota and Lexus vehicles, can be temporarily disabled through an undocumented series of brake pedal and handbrake operations. Furthermore, unplugging a wheel speed sensor is another method of disabling most ESC systems. The ESC implementation on newer Ford vehicles cannot be completely disabled even through the use of the "off switch". The ESC will automatically reactivate at highway speeds, and below that if it detects a skid with the brake pedal depressed.

Availability and cost

ESC is built on top of an anti-lock brake (ABS) system, and all ESC-equipped vehicles are fitted with traction control. The ESC components include a yaw rate sensor, a lateral acceleration sensor, a steering wheel sensor, and an upgraded integrated control unit. According to National Highway Traffic Safety Administration research, ABS in 2005 cost an estimated US$368; ESC cost a further US$111. The retail price of ESC varies; as a stand-alone option it retails for as little as $250 USD. However, ESC is rarely offered as a sole option, and is generally not available for aftermarket installation. Instead, it is frequently bundled it with other features or more expensive trims, so the cost of a package that includes ESC could be several thousand dollars. Nonetheless, ESC is considered highly cost-effective and it might pay for itself in reduced insurance premiums. When new federal regulations requiring a safety tool called electronic stability control kick in during 2012, all cars will employ it.

Availability of ESC in passenger vehicles varies between manufacturers and countries. In 2007, ESC was available in roughly 50% of new North American models compared to about 75% in Sweden. However, consumer awareness affects buying patterns so that roughly 45% of vehicles sold in North America and the UK are purchased with ESC, contrasting with 78-96% in other European countries such as Germany, Denmark, and Sweden. While few vehicles had ESC prior to 2004, increased awareness will increase the number of vehicles with ESC on the used car market.

ESC is available on cars, SUVs and pickup trucks from all major auto makers. Luxury cars, sports cars, SUVs, and crossovers are usually equipped with ESC. Midsize cars are also gradually catching on, though the 2008 model years of the, Nissan Altima and Ford Fusion only offered ESC on their V6 engine-equipped cars. While ESC includes traction control, there are vehicles such as the 2008 Chevrolet Malibu LS and 2008 Mazda6 that have traction control but not ESC. ESC is rare among subcompact cars as of 2008. The 2009 Toyota Corolla in the United States (but not Canada) has stability control as a $250 option on all trims below that of the XRS which has it as standard. In Canada, for the 2010 Mazda3, ESC is as an option on the midrange GS trim as part of the moonroof package, and is standard on the top-of-the-line GT version. The 2009 Ford Focus has ESC as an option for the S and SE models, and standard on the SEL and SES models

ESC is also available on some motor homes. Elaborate ESC and ESP systems (including Roll Stability Control (RSC)) are available for many commercial vehicles, including transport trucks, trailers, and buses from manufacturers such as Bendix Corporation, WABCO Daimler, Scania AB, and Prevost, and light passenger vehicles.

The *ChooseESC!* campaign, run by the EU's *eSafetyAware!* project, provides a global perspective on ESC. One *ChooseESC!* publication shows the availability of ESC in EU member countries.

In the US, the Insurance Institute for Highway Safety (IIHS) website shows availability of ESC in individual US models and the National Highway Traffic Safety Administration (NHTSA website) lists US models with ESC.

In Australia, the *National Roads and Motorists' Association* NRMA shows the availability of ESC in Australian models.

Future

The market for ESC is growing quickly, especially in European countries such as Sweden, Denmark, and Germany. For example, in 2003 in Sweden the purchase rate on new cars with ESC was 15%. The Swedish road safety administration issued a strong ESC recommendation and in September 2004, 16 months later, the purchase rate was 58%. A stronger ESC recommendation was then given and in December 2004, the purchase rate on new cars had reached 69% and by 2008 it had grown to 96%. ESC advocates around the world are promoting increased ESC use through legislation and public awareness campaigns and by 2012, most new vehicles should be equipped with ESC.

Just as ESC is founded on the Anti-lock braking system (ABS), ESC is the foundation for new advances such as Roll Stability Control (RSC) that works in the vertical plane much like ESC works in the horizontal plane. When RSC detects impending rollover (usually on transport trucks or SUVs), RSC applies brakes, reduces throttle, induces understeer, and/or slows down the vehicle.

The computing power of ESC facilitates the networking of active and passive safety systems, addressing other causes of crashes. For example, sensors may detect when a vehicle is following too closely and slow down the vehicle, straighten up seat backs, and tighten seat belts, avoiding and/or preparing for a crash.

Regulation

While Sweden used public awareness campaigns to promote ESC use, others implemented or proposed legislation.

The Canadian province of Quebec was the first jurisdiction to implement an ESC law, making it compulsory for carriers of dangerous goods (without data recorders) in 2005.

The United States was next, requiring ESC for all passenger vehicles under 10,000 pounds (4536 kg), phasing in the regulation starting with 55% of 2009 models (effective 1 September 2008), 75% of 2010 models, 95% of 2011 models, and all 2012 models.

Canada will require all new passenger vehicles to have ESC from 1 September 2011.

The Australian Government announced on 23 June 2009 that ESC would be compulsory from 1 November 2011 for all new passenger vehicles sold in Australia, and for all new vehicles from November 2013.

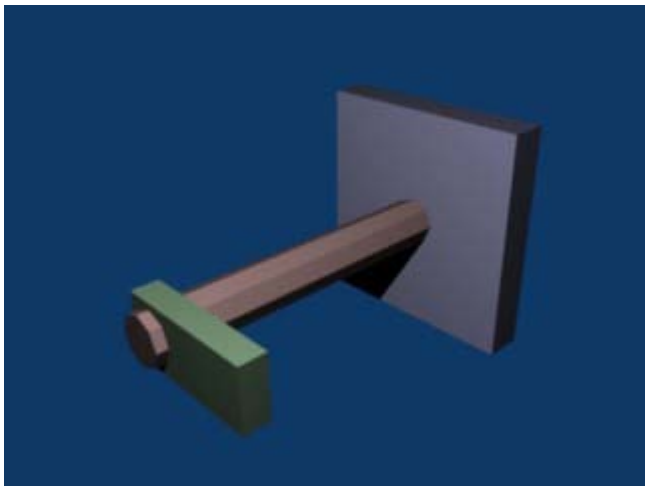
The European Parliament has also called for the accelerated introduction of ESC. The European Commission has confirmed a proposal for the mandatory introduction of ESC on all new cars and commercial vehicle models sold in the EU from 2012, with all new cars being equipped by 2014.

The United Nations Economic Commission for Europe has passed a Global Technical Regulation to harmonize ESC standards.

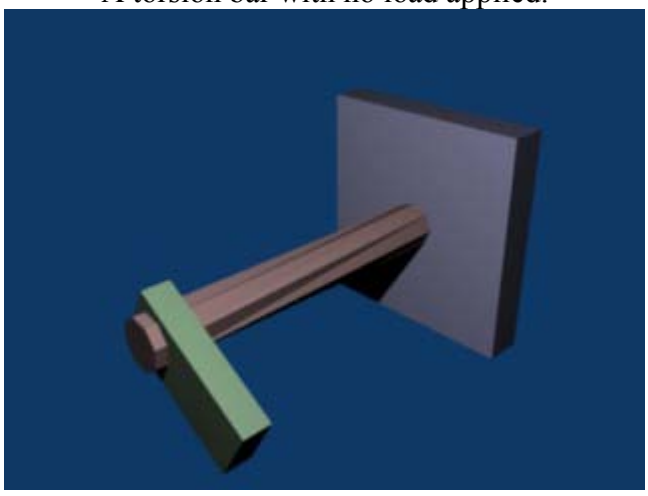
Chapter 11

Torsion Bar Suspension and Swing Axle

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 reclocked 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 flexibilty 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

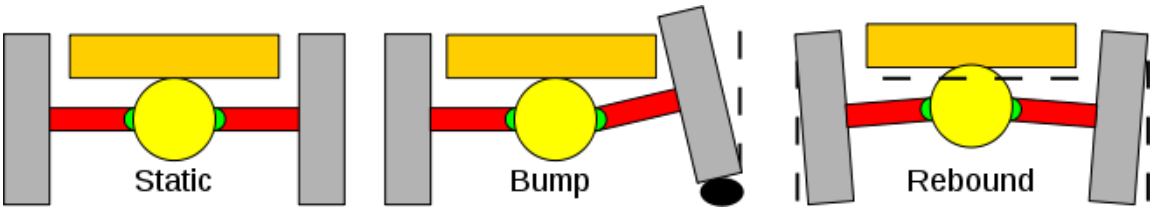
Some front-wheel drive automobiles use a related type of torsion beam suspension, usually called a twist beam rear suspension, in which the rear wheels are carried on trailing arms connected by a laterally mounted torsion beam. The torsion beam functions both as wheel locating arm and as an anti-roll 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.

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

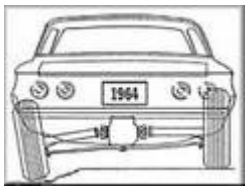
Shortcomings

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.