

Automotive Technology

Level 5 Automotive & Transport Design

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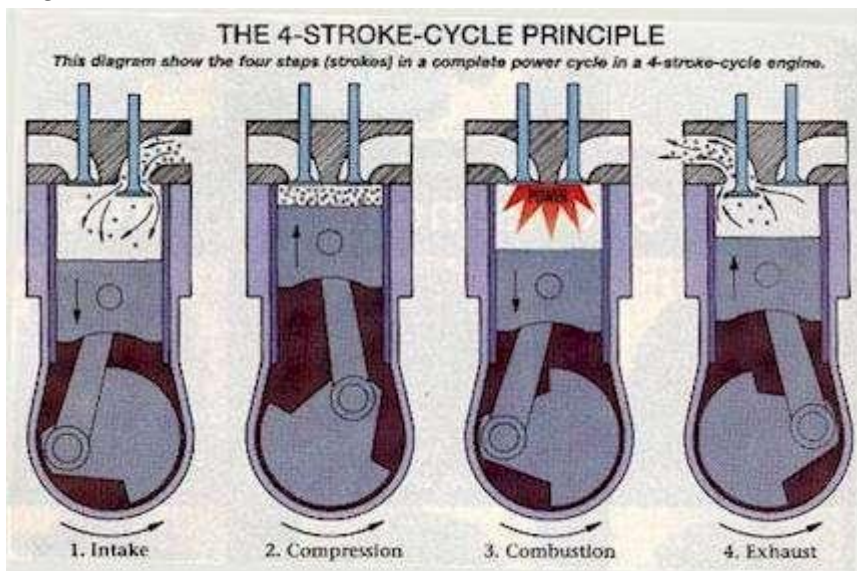
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Automotive Petrol Engine

Almost all cars currently use what is called a **four-stroke combustion cycle** to convert gasoline into motion. The four-stroke approach is also known as the **Otto cycle**, in honour of Nikolaus Otto, who invented it in 1867. The four strokes are illustrated in **Figure 1**. They are:

- The intake stroke.
- The compression stroke.
- The combustion stroke
- The exhaust stroke.

This diagram shows the four steps (strokes) in a complete power cycle in a 4-stroke-cycle engine.



- 1. On the downstroke, the intake valve is opened and the fuel/air mixture is drawn into the combustion chamber.*
- 2. On the upstroke, the intake valve has closed and the fuel/air mixture undergoes compression.*
- 3. Ignition takes place by means of the glow plug (not shown); the fuel/air mix explodes, and the piston is forced down for the second time in the cycle. This is called the "power stroke".*
- 4. The exhaust valve is open and the piston moves up for the second time in the cycle, and the burned gases are expelled out through the exhaust valve into the exhaust.*

The piston is connected to the **crank shaft** by a **connecting rod**. As the crankshaft revolves, it has the effect of "resetting the cannon." Here's what happens as the engine goes through its cycle:

- The piston starts at the top, the intake valve opens, and the piston moves down to let the engine take in a cylinder full of air and gasoline. This is the **intake stroke**. Only the tiniest drop of gasoline needs to be mixed into the air for this to work. (Part 1 of the figure)
- Then the piston moves back up to compress this fuel/air mixture. **Compression** makes the explosion more powerful. (Part 2 of the figure)
- When the piston reaches the top of its stroke, the spark plug emits a spark to ignite the gasoline. The gasoline charge in the cylinder **explodes**, driving the piston down. (Part 3 of the figure)
- Once the piston hits the bottom of its stroke, the exhaust valve opens and the **exhaust** leaves the cylinder to go out the tail pipe. (Part 4 of the figure)

Now the engine is ready for the next cycle, so it intakes another charge of air and gas. ... Notice that the motion that comes out of an internal combustion engine is **rotational**, while the motion produced by a potato cannon is **linear** (straight). In an engine the linear motion is converted into rotational motion by the crank shaft. The rotational motion is nice because we plan to turn (rotate) the car's wheels with it anyway. Almost all cars today use a reciprocating internal combustion engine because this engine is:

- relatively efficient (compared to an external combustion engine)
- relatively inexpensive (compared to a gas turbine)
- relatively easy to refuel (compared to an electric car)

Parts of an Engine

Let's use the same diagram you saw in the previous article on internal combustion to identify all of the different parts in a simple 4-cycle engine

Here's a quick description of each one, along with a lot of vocabulary that will help you understand what all the car ads are talking about.

Cylinder

The core of the engine is the cylinder. The piston moves up and down inside the cylinder. The engine described here has one cylinder. That is typical of most lawn mowers, but most cars have more than one cylinder (four, six and eight cylinders are common). In a multi-cylinder engine the cylinders usually are arranged in one of three ways: **inline**, **V** or **flat** (also known as horizontally opposed or boxer), as shown in the following figures.



Figure 2. Inline -- the cylinders are arranged in a line in a single bank.

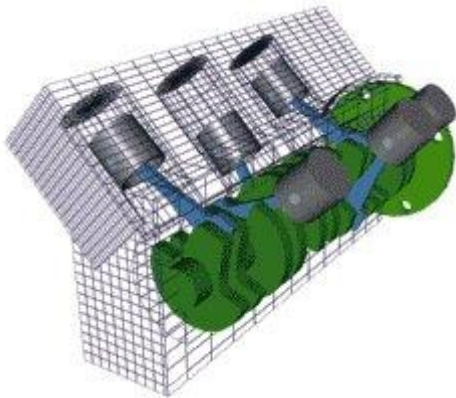


Figure 3. V -- the cylinders are arranged in two banks set at an angle to one another.

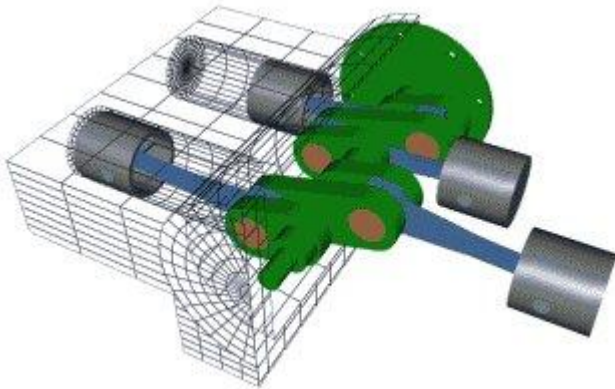


Figure 4. Flat -- the cylinders are arranged in two banks on opposite sides of the engine. Different configurations have different smoothness, manufacturing-cost and shape characteristics that make them more suitable in some vehicles.

Spark plug

The spark plug supplies the spark that ignites the air/fuel mixture so that combustion can occur. The spark must happen at just the right moment for things to work properly.

Valves

The intake and exhaust valves open at the proper time to let in air and fuel and to let out exhaust. Note that both valves are closed during compression and combustion so that the combustion chamber is sealed.

Piston

A piston is a cylindrical piece of metal that moves up and down inside the cylinder.

Piston rings

Piston rings provide a sliding seal between the outer edge of the piston and the inner edge of the cylinder. The rings serve two purposes:

- They prevent the fuel/air mixture and exhaust in the combustion chamber from leaking into the sump during compression and combustion.
- They keep oil in the sump from leaking into the combustion area, where it would be burned and lost.

Most cars that "burn oil" and have to have a quart added every 1,000 miles are burning it because the engine is old and the rings no longer seal things properly.

Combustion

chamber

The combustion chamber is the area where compression and combustion take place. As the piston moves up and down, you can see that the size of the combustion chamber changes. It has some maximum volume as well as a minimum volume. The difference between the maximum and minimum is called the **displacement** and is measured in liters or CCs (Cubic Centimeters, where 1,000 cubic centimeters equals a liter). So if you have a 4-cylinder engine and each cylinder displaces half a liter, then the entire engine is a "2.0 liter engine." If each cylinder displaces half a liter and there are six cylinders arranged in a V configuration, you have a "3.0 liter V-6." Generally, the displacement tells you something about how much power an engine has. A cylinder that displaces half a liter can hold twice as much fuel/air mixture as a cylinder that displaces a quarter of a liter, and therefore you would expect about twice as much power from the larger cylinder (if everything else is equal). So a 2.0 liter engine is roughly half as powerful as a 4.0 liter engine. You can get more displacement either by increasing the number of cylinders or by making the combustion chambers of all the cylinders bigger (or both).

Connecting rod

The connecting rod connects the piston to the crankshaft. It can rotate at both ends so that its angle can change as the piston moves and the crankshaft rotates.

Crank shaft

The crank shaft turns the piston's up and down motion into circular motion just like a crank on a jack-in-the-box does.

Sump

The sump surrounds the crankshaft. It contains some amount of oil, which collects in the bottom of the sump (the oil pan).

Engine Systems

As you can see in the previous section an engine has a number of systems that help it do its job of converting fuel into motion. Most of these subsystems can be implemented using different technologies, and better technologies can improve the performance of the engine. Here's a look at all of the different subsystems used in modern engines:

Valve train

The valve train consists of the valves and a mechanism that opens and closes them. The opening and closing system is called a **cam shaft**. The cam shaft has lobes on it that move the valves up and down, as shown in **Figure 5**.

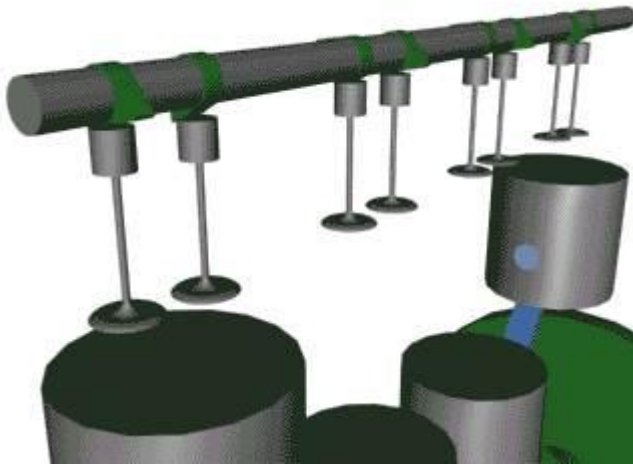


Figure 5. The cam shaft.

Most modern engines have what are called **overhead cams**. This means that the cam shaft is located above the valves, as you see in Figure 5. The cams on the shaft activate the valves directly or through a very short linkage. Older engines used a cam shaft located in the sump near the crankshaft. **Rods** linked the cam below to **valve lifters** above the valves. This approach has more moving parts and also causes more lag between the cam's activation of the valve and the valve's subsequent motion. A **timing belt** or timing chain links the crankshaft to the cam shaft so that the valves are in sync with the pistons. The cam shaft is **geared** to turn at one-half the rate of the crankshaft. Many high-performance engines have four valves per cylinder (two for intake, two for exhaust), and this arrangement requires two cam shafts per bank of cylinders, hence the phrase "dual overhead cams."

The camshaft uses lobes, called **cams**, that push against the valves to open them as the camshaft rotates; springs on the valves return them to their closed position. This is a critical job, and can have a great impact on an engine's performance at different speeds. The key parts of any camshaft are the **lobes**. As the camshaft spins, the lobes open and close the intake and exhaust valves in time with the motion of the piston. It turns out that there is a direct relationship between the way the shape of the cam lobes and the way the engine performs in different speed (revolutions per minute or RPM) ranges.

To understand why this is the case, imagine that we are running an engine extremely slowly -- at just 10 or 20 RPM -- so that it takes the piston a couple of seconds to complete a cycle. It would be impossible to actually run a normal engine this slowly, but let's imagine that we could. At this slow speed, we would want cam lobes shaped so that:

- Just as the piston starts moving downward in the intake stroke (called top dead center, or TDC), the intake valve would open. The intake valve would close right as the piston bottoms out.
- Then the exhaust valve would open right as the piston bottoms out (called bottom dead center, or BDC) at the end of the combustion stroke, and would close as the piston completes the exhaust stroke.

This set-up would work really well for the engine as long as it ran at this very slow speed. When you increase the RPM, however, this configuration for the camshaft does not work well. If the engine is running at 4,000 RPM, the valves are opening and closing 2,000 times every minute, or 33 times every second. At these speeds, the piston is moving very quickly, so the air/fuel mixture rushing into the cylinder is moving very quickly as well.

When the intake valve opens and the piston starts its intake stroke, the air/fuel mixture in the intake runner starts to accelerate into the cylinder. By the time the piston reaches the bottom of its intake stroke, the air/fuel is moving at a pretty high speed. If we were to slam the intake valve shut, all of that air/fuel would come to a stop and not enter the cylinder. By leaving the intake valve open a little longer, the momentum of the fast-moving air/fuel continues to force air/fuel into the cylinder as the piston starts its compression stroke. So the faster the engine goes, the faster the air/fuel moves, and the longer we want the intake valve to stay open. We also want the valve to open wider at higher speeds. This parameter, called **valve lift**, is governed by the cam lobe profile.

Any given camshaft will be perfect only at one engine speed. At every other engine speed, the engine won't perform to its full potential. A fixed camshaft is, therefore, always a compromise. This is why car makers have developed schemes to vary the cam profile as the engine speed changes.

Camshaft Arrangements

There are several different arrangements of camshafts on engines:

- single overhead cam (SOHC)
- double overhead cam (DOHC)
- pushrod

Single Overhead Cams

This arrangement denotes an engine with **a single cam per head**. So if it is an inline 4-cylinder or inline 6-cylinder engine, it will have one cam; if it is a V-6 or V-8, it will have two cams (one for each head). As shown in Figure 5.

The cam actuates rocker arms that press down on the valves, opening them. Springs return the valves to their closed position. These springs have to be very strong because at high engine speeds, the valves are pushed down very quickly, and it is the springs that keep the valves in contact with the rocker arms. If the springs were not strong enough, the valves might come away from the rocker arms and snap back. This is an undesirable situation that would result in extra wear on the cams and rocker arms.

On single and double overhead cam engines, the cams are driven by the crankshaft, via either a belt or chain called the **timing belt** or **timing chain**. These belts and chains need to be replaced or adjusted at regular intervals. If a timing belt breaks, the cam will stop spinning and the piston could hit the open valves.

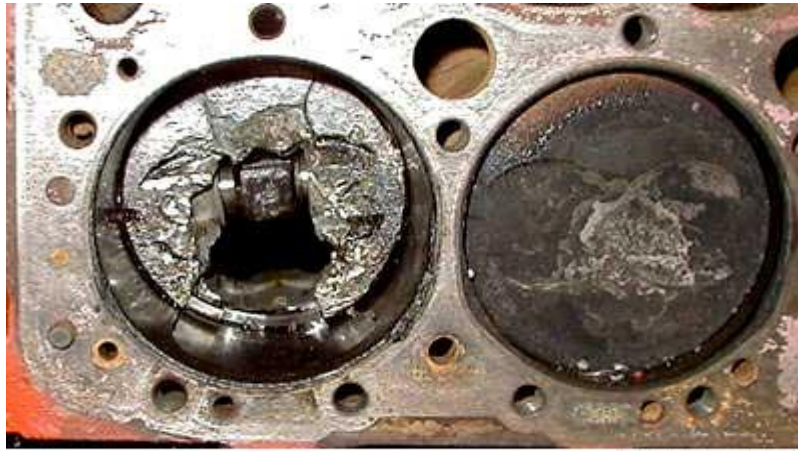


Figure 3. Damage from a piston striking a valve

Figure 3 shows what can happen when a piston hits an open valve.

Double Overhead Cam

A double overhead cam engine has **two cams per head**. So inline engines have two cams, and V engines have four. Usually, double overhead cams are used on engines with four (or more) valves per cylinder -- a single camshaft simply cannot fit enough cam lobes to actuate all of those valves.

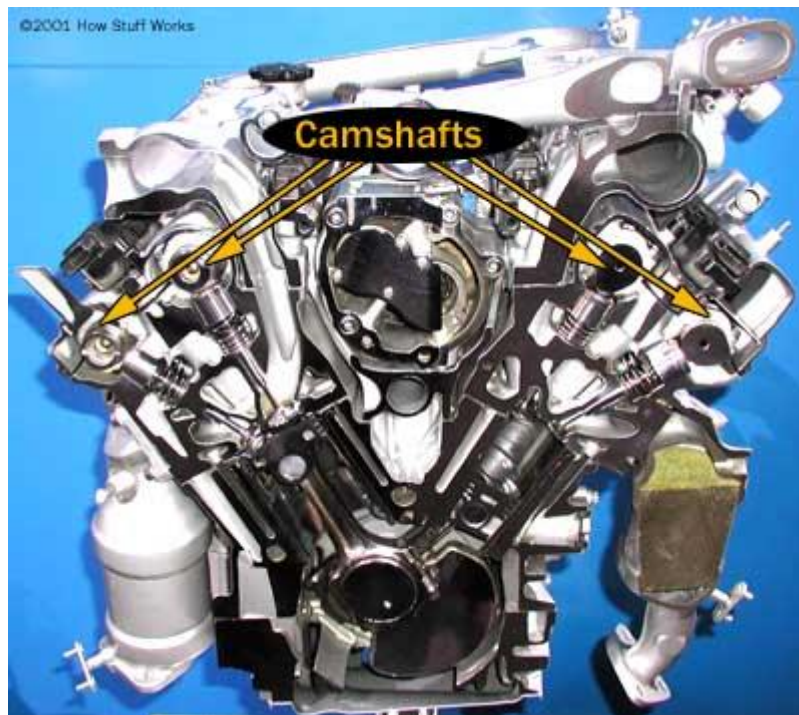


Figure 4. A cutaway view of a double overhead cam engine.

The main reason to use double overhead cams is to allow for more intake and exhaust valves. More valves means that intake and exhaust gases can flow more freely because there are more openings for them to flow through. This increases the power of the engine.

Pushrod Engines

Like SOHC and DOHC engines, the valves in a pushrod engine are located in the head, above the cylinder. **The key difference is that the camshaft on a pushrod engine is inside the engine block, rather than in the head.**



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Figure 5. A pushrod engine

The cam actuates long rods that go up through the block and into the head to move the rockers. These long rods add mass to the system, which increases the load on the valve springs. This can limit the speed of pushrod engines; the overhead camshaft, which eliminates the pushrod from the system, is one of the engine technologies that made higher engine speeds possible.

The camshaft in a pushrod engine is often driven by [gears](#) or a short chain. Gear-drives are generally less prone to breakage than belt drives, which are often found in overhead cam engines.

Ignition system

The ignition system (**Figure 6**) produces a high-voltage electrical charge and transmits it to the spark plugs via **ignition wires**. The charge first flows to a **distributor**, which you can easily find under the hood of most cars. The distributor has one wire going in the center and four, six, or eight wires (depending on the number of cylinders) coming out of it. These **ignition wires** send the charge to each spark plug. The engine is timed so that only one

cylinder receives a spark from the distributor at a time. This approach provides maximum smoothness.

Cooling system

The cooling system in most cars consists of the radiator and water pump. Water circulates through passages around the cylinders and then travels through the radiator to cool it off. In a few cars (most notably Volkswagen Beetles), as well as most motorcycles and lawn mowers, the engine is air-cooled instead (You can tell an air-cooled engine by the fins adorning the outside of each cylinder to help dissipate heat). Air-cooling makes the engine lighter but hotter, generally decreasing engine life and overall performance.

Although [Petrol engines](#) have improved a lot, they are still not very efficient at turning chemical energy into mechanical power. Most of the energy in the gasoline (perhaps 70%) is converted into heat, and it is the job of the **cooling system** to take care of that heat. In fact, the cooling system on a [car](#) driving down the motorway dissipates enough heat to heat two average-sized houses! The primary job of the cooling system is to keep the engine from overheating by transferring this heat to the air, but the cooling system also has several other important jobs.

The [engine](#) in your car runs best at a fairly high temperature. When the engine is cold, components wear out faster, and the engine is less efficient and emits more pollution. So another important job of the cooling system is to allow the engine to heat up as quickly as possible, and then to keep the engine at a constant temperature.

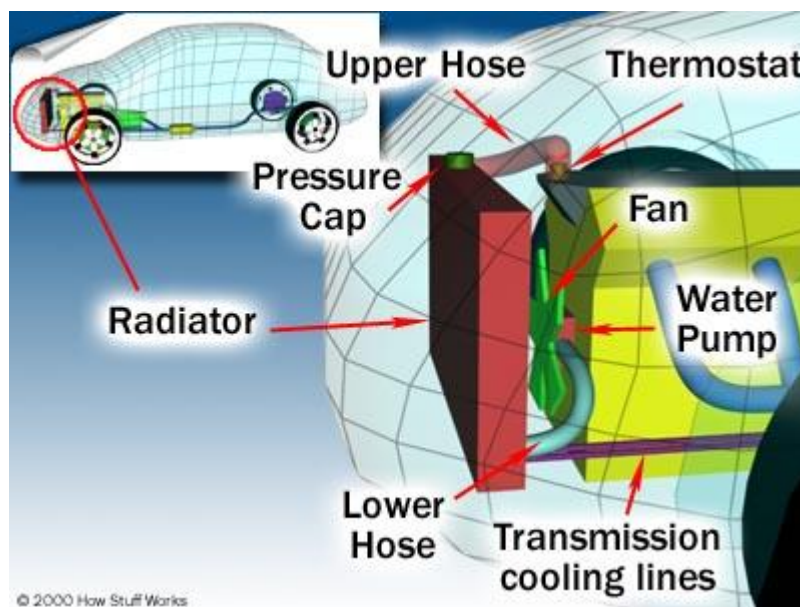


Diagram of a cooling system showing how all the plumbing is connected.

Inside your car's engine, fuel is constantly burning. A lot of the heat from this combustion goes right out the exhaust system, but some of it soaks into the engine, heating it up. The engine runs best when its coolant is about 93 degrees Celsius. At this temperature:

- The combustion chamber is hot enough to completely vaporize the fuel, providing better combustion and reducing emissions.
- The oil used to lubricate the engine has a lower viscosity (it is thinner), so the engine parts move more freely and the engine wastes less power moving its own components around.
- Metal parts wear less.

There are two types of cooling systems found on cars: liquid-cooled and air-cooled.

Air Cooling

Some older cars, and very few modern cars, are air-cooled. Instead of circulating fluid through the engine, the engine block is covered in aluminium fins that conduct the heat away from the cylinder. A powerful fan forces air over these fins, which cools the engine by transferring the heat to the air.

Liquid Cooling

The cooling system on liquid-cooled cars circulates a fluid through pipes and passageways in the engine. As this liquid passes through the hot engine it absorbs heat, cooling the engine. After the fluid leaves the engine, it passes through a heat exchanger, or radiator, which transfers the heat from the fluid to the air blowing through the exchanger.

The cooling system in your car has a lot of plumbing. We'll start at the **pump** and work our way through the system. The **pump** sends the fluid into the **engine block**, where it makes its way through passages in the engine around the cylinders. Then it returns through the **cylinder head** of the engine. The **thermostat** is located where the fluid leaves the engine. The plumbing around the **thermostat** sends the fluid back to the pump directly if the thermostat is closed. If it is open, the fluid goes through the **radiator** first and then back to the **pump**.

There is also a separate circuit for the heating system. This circuit takes fluid from the cylinder head and passes it through a heater core and then back to the pump.

On cars with automatic transmissions, there is normally also a separate circuit for cooling the transmission fluid built into the radiator. The oil from the transmission is pumped by the transmission through a second heat exchanger inside the **radiator**.

Fluid

Cars operate in a wide variety of temperatures, from well below freezing to well over 100 F (38 C). So whatever fluid is used to cool the engine has to have a very low freezing point, a high boiling point, and it has to have the capacity to hold a lot of heat.

Water is one of the most effective fluids for holding heat, but water freezes at too high a temperature to be used in car engines. The fluid that most cars use is a mixture of water and ethylene glycol (C₂H₆O₂), also known as antifreeze. By adding ethylene glycol to water, the boiling and freezing points are improved significantly.

	Pure Water	50/50 C ₂ H ₆ O ₂ /Water	70/30 C ₂ H ₆ O ₂ /Water
Freezing Point	0 C / 32 F	-37 C / -35 F	-55 C / -67 F
Boiling Point	100 C / 212 F	106 C / 223 F	113 C / 235 F

The temperature of the coolant can sometimes reach 250 to 275 F (121 to 135 C). Even with ethylene glycol added, these temperatures would boil the coolant, so something additional must be done to raise its boiling point.

The cooling system uses **pressure** to further raise the boiling point of the coolant. Just as the boiling temperature of water is higher in a pressure cooker, the boiling temperature of coolant is higher if you pressurize the system. Most cars have a 14 to 15 pounds per square inch (psi) pressure limit, which raises the boiling point another (25 C), so the coolant can withstand the high temperatures.

Antifreeze also contains additives to resist corrosion.

Water Pump

The water pump is a simple centrifugal pump driven by a belt connected to the crankshaft of the engine. The pump circulates fluid whenever the engine is running. The water pump uses centrifugal force to send fluid to the outside while it spins, causing fluid to be drawn from the center continuously. The inlet to the pump is located near the center so that fluid returning from the radiator hits the pump vanes. The pump vanes fling the fluid to the outside of the pump, where it can enter the engine.

The fluid leaving the pump flows first through the engine block and cylinder head, then into the radiator and finally back to the pump.

Engine

The engine block and cylinder head have many passageways cast or machined in them to allow for fluid flow. These passageways direct the coolant to the most critical areas of the engine.



Note that the walls of the cylinder are quite thin, and that the engine block is mostly hollow.

Temperatures in the combustion chamber of the engine can reach 2500 C, so cooling the area around the cylinders is critical. Areas around the exhaust valves are especially crucial, and almost all of the space inside the cylinder head around the valves that is not needed for structure is filled with coolant. If the engine goes without cooling for very long, it can seize. When this happens, the metal has actually gotten hot enough for the piston to weld itself to the cylinder. This usually means the complete destruction of the engine.



The head of the engine also has large coolant passageways.

One interesting way to reduce the demands on the cooling system is to reduce the amount of heat that is transferred from the combustion chamber to the metal parts of the engine. Some engines do this by coating the inside of the top of the cylinder head with a thin layer of ceramic. Ceramic is a poor conductor of heat, so less heat is conducted through to the metal, and more passes out of the exhaust.

Radiator

A radiator is a type of heat exchanger. It is designed to transfer heat from the hot coolant that flows through it to the air blown through it by the fan.

Most modern cars use aluminum radiators. These radiators are made by brazing thin aluminum fins to flattened aluminum tubes. The coolant flows from the inlet to the outlet through many tubes mounted in a parallel arrangement. The fins conduct the heat from the tubes and transfer it to the air flowing through the radiator.

The tubes sometimes have a type of fin inserted into them called a **turbulator**, which increases the turbulence of the fluid flowing through the tubes. If the fluid flowed very smoothly through the tubes, only the fluid actually touching the tubes would be cooled directly. The amount of heat transferred to the tubes from the fluid running through them depends on the difference in temperature between the tube and the fluid touching it. So if the fluid that is in contact with the tube cools down quickly, less heat will be transferred. By creating turbulence inside the tube, all of the fluid mixes together, keeping the temperature of the fluid touching the tubes up so that more heat can be extracted, and all of the fluid inside the tube is used effectively.

Pressure Cap

The radiator cap actually increases the boiling point of your coolant by about (25 C). How does this simple cap do this? The same way a pressure cooker increases the boiling temperature of water. The cap is actually a pressure release valve, and on cars it is usually set to 15 psi. The boiling point of water increases when the water is placed under pressure.

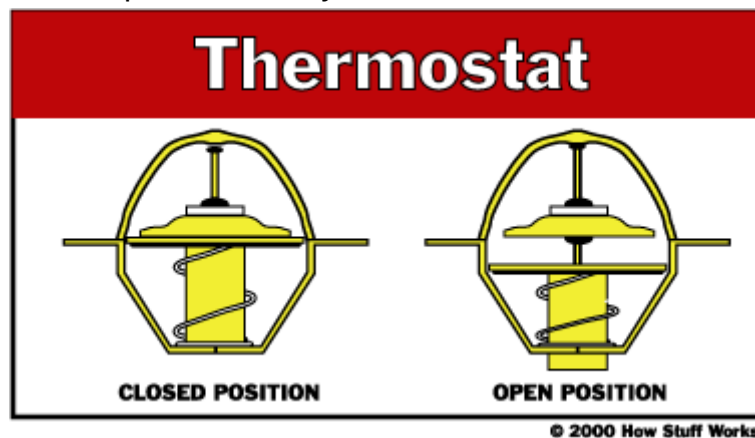
When the fluid in the cooling system heats up, it expands, causing the pressure to build up. The cap is the only place where this pressure can escape, so the setting of the spring

on the cap determines the maximum pressure in the cooling system. When the pressure reaches 15 psi, the pressure pushes the valve open, allowing coolant to escape from the cooling system. This coolant flows through the overflow tube into the bottom of the overflow tank. This arrangement keeps air out of the system. When the radiator cools back down, a vacuum is created in the cooling system that pulls open another spring loaded valve, sucking water back in from the bottom of the overflow tank to replace the water that was expelled.

Thermostat

The thermostat's main job is to allow the engine to heat up quickly, and then to keep the engine at a constant temperature. It does this by regulating the amount of water that goes through the radiator. At low temperatures, the outlet to the radiator is completely blocked -- all of the coolant is recirculated back through the engine.

Once the temperature of the coolant rises to between 180 to 195 F, the thermostat starts to open, allowing fluid to flow through the radiator. By the time the coolant reaches 200 to 218 F, the thermostat is open all the way.



The open and closed positions of a thermostat

The secret of the thermostat lies in the small cylinder located on the engine-side of the device. This cylinder is filled with a wax that begins to melt at around 180 F (different thermostats open at different temperatures, but 180 F is a common one). A rod connected to the valve presses into this wax. When the wax melts, it expands significantly, pushing the rod out of the cylinder and opening the valve. a good bit more because it is changing from a solid to a liquid in addition to expanding from the heat.

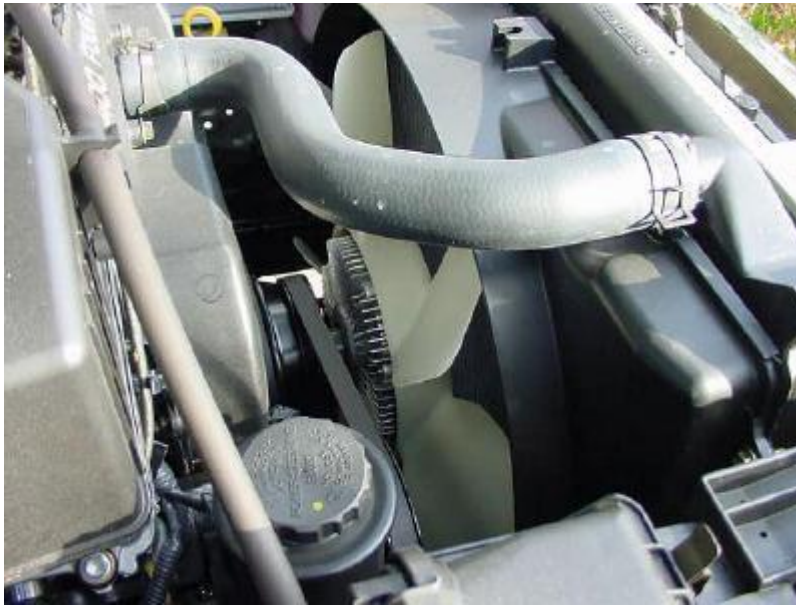
Fan

Like the thermostat, the cooling fan has to be controlled so that it allows the engine to maintain a constant temperature.

Front wheel drive cars have electric fans because the engine is usually mounted transversely, meaning the output of the engine points toward the side of the car. The fans are controlled either with a thermostatic switch or by the engine computer, and they turn on when the temperature of the coolant goes above a set point. They turn back off when the temperature drops below that point.

Rear wheel drive cars with longitudinal engines usually have engine-driven cooling fans. These fans have a thermostatically controlled viscous [clutch](#). This clutch is positioned at the hub of the fan, in the airflow coming through the radiator. This special viscous clutch is much like the [viscous coupling](#) sometimes found in all-wheel drive cars. The fluid in the clutch gets thicker as it heats up, causing the fan to spin faster to catch up with the engine

rotation. When the car is cold, the fluid in the clutch remains cold and the fan spins slowly, allowing the engine to quickly warm up to its proper operating temperature.



Cooling fan

Heating System

You may have heard the advice that if your car is overheating, open all the windows and run the heater with the fan going at full blast. This is because the heating system is actually a secondary cooling system that mirrors the main cooling system on your car.



Heater plumbing

The heater core, which is located in the dashboard of your car, is really a small radiator. The heater fan blows air through the heater core and into the passenger compartment of your car.



A heater core looks like a small radiator.

The heater core draws its hot coolant from the cylinder head and returns it to the pump -- so the heater works regardless of whether the thermostat is open or closed

Starting System

The starting system consists of an electric starter motor and a **starter solenoid**. When you turn the ignition key, the starter motor spins the engine a few revolutions so that the combustion process can start. It takes a powerful motor to spin a cold engine. The starter motor must overcome:

- All of the internal friction caused by the piston rings.
- The compression pressure of any cylinder(s) that happens to be in the compression stroke.
- The energy needed to open and close valves with the cam shaft.
- All of the "other" things directly attached to the engine, like the water pump, oil pump, alternator, etc.

Because so much energy is needed and because a car uses a 12-volt electrical system, hundreds of amps of electricity must flow into the starter motor. The start solenoid is essentially a large electronic switch that can handle that much current. When you turn the ignition key, it activates the solenoid to power the motor.

Lubrication System

The lubrication system makes sure that every moving part in the engine gets oil so that it can move easily. The two main parts needing oil are the pistons (so they can slide easily in their cylinders) and any bearings that allow things like the crankshaft and cam shafts to rotate freely. In most cars oil is sucked out of the oil pan by the oil pump, run through the oil filter to remove any grit, and then squirted under high pressure onto bearings and the cylinder walls. The oil then trickles down into the sump, where it is collected again and the cycle repeats.

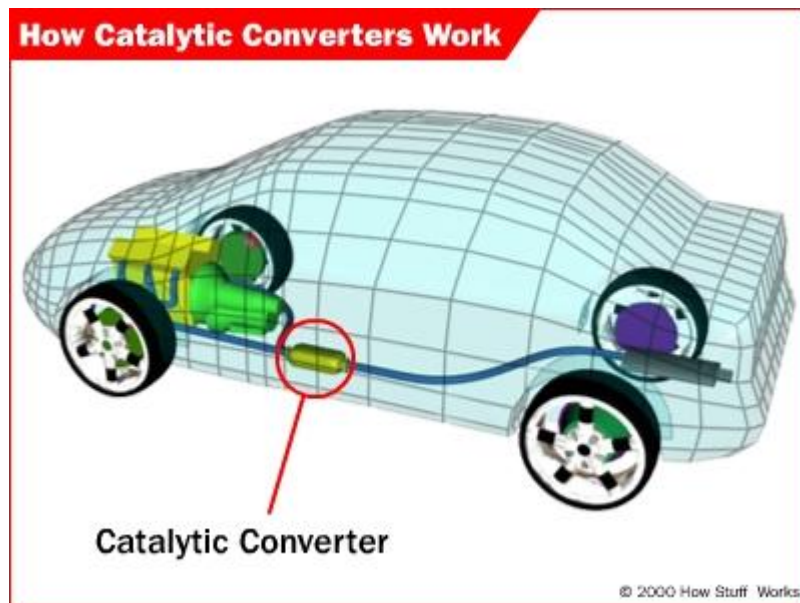
Fuel System

The fuel system pumps gas from the gas tank and mixes it with air so that the proper air/fuel mixture can flow into the cylinders. Fuel is delivered in three common ways: carburetion, port fuel injection and direct fuel injection.

- In carburetion a device called a **carburetor** mixes gas into air as the air flows into the engine.
- In a fuel injected engine the right amount of fuel is injected individually into each cylinder either right above the intake valve (port fuel injection) or directly into the cylinder (direct fuel injection).

Exhaust System

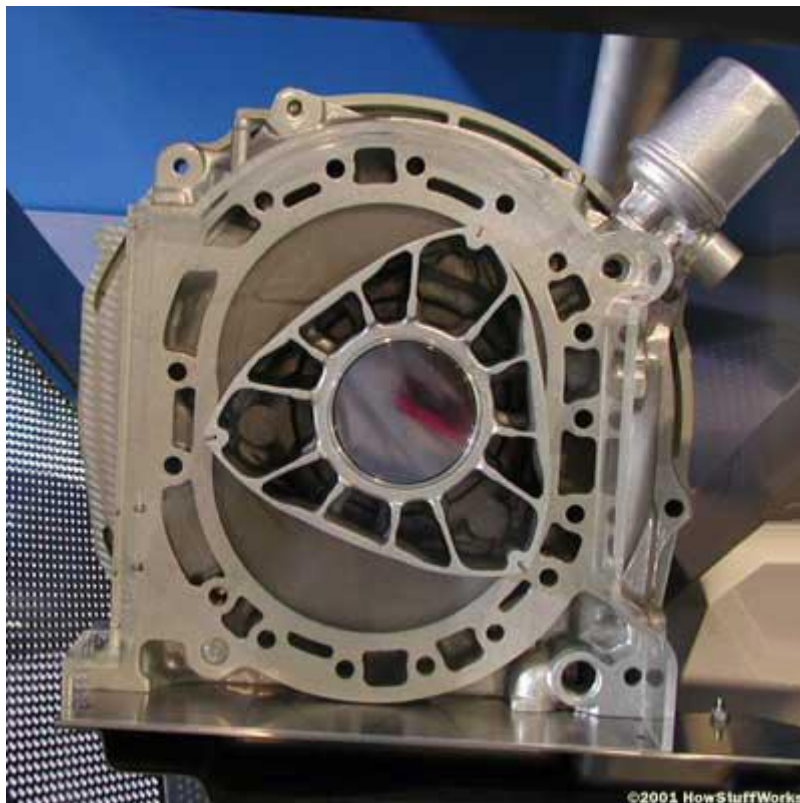
The exhaust system includes the exhaust pipe and the muffler. Without a muffler what you would hear is the sound of thousands of small explosions coming out your tailpipe. A muffler dampens the sound. The exhaust system also includes a catalytic converter. There are millions of cars on the road in the U.S., and each one is potentially a source of air pollution. Especially in large cities, the amount of pollution that all the cars produce together can create big problems. To solve those problems, cities, states and the federal government create clean-air laws, and many laws have been enacted that restrict the amount of pollution that [cars](#) can produce. To keep up with these laws, automakers have made many refinements to car [engines](#) and fuel systems. To help reduce the emissions further, they have developed an interesting device called a **catalytic converter**, which treats the exhaust before it leaves the car and removes a lot of the pollution.



Location of catalytic converter in car.

Rotary Engine

A rotary engine is an internal combustion engine, like the [engine](#) in your car, but it works in a completely different way than the conventional piston engine.



The rotor and housing of a rotary engine from a Mazda RX-7. These parts replace the pistons, cylinders, valves, connecting rods and camshafts found in piston engines.

In a piston engine, the same volume of space (the cylinder) alternately does four different jobs -- intake, compression, combustion and exhaust. A rotary engine does these same four jobs, but each one happens in its own part of the housing. It's kind of like having a dedicated cylinder for each of the four jobs, with the piston moving continually from one to the next.

Like a piston engine, the rotary engine uses the pressure created when a combination of air and fuel is burned. In a piston engine, that pressure is contained in the cylinders and forces pistons to move back and forth. The connecting rods and crankshaft convert the reciprocating motion of the pistons into rotational motion that can be used to power a car.

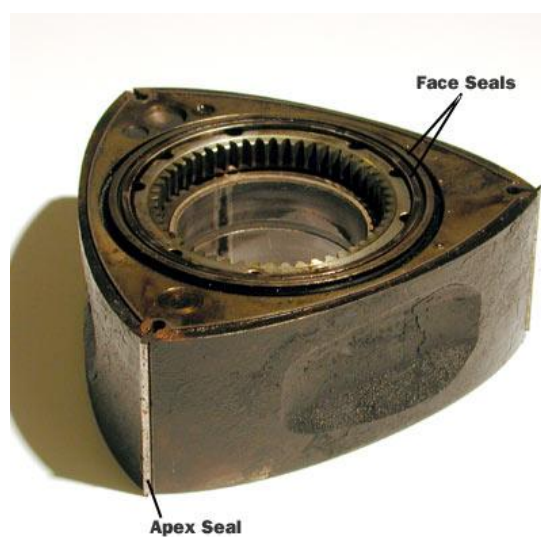
In a rotary engine, the pressure of combustion is contained in a chamber formed by part of the housing and sealed in by one face of the triangular rotor, which is what the engine uses instead of pistons. The rotor follows a path that looks like something you'd create with a spirograph. This path keeps each of the three peaks of the rotor in contact with the housing, creating three separate volumes of gas. As the rotor moves around the chamber, each of the three volumes of gas alternatively expands and contracts. It is this expansion and contraction that draws air and fuel into the engine, compresses it and makes useful power as the gases expand and then expels the exhaust. The rotary engine (originally conceived and developed by Dr. Felix Wankel) is sometimes called a **Wankel engine**, or **Wankel rotary engine**.

The Parts of a Rotary Engine

A rotary engine has an [ignition system](#) and a [fuel-delivery system](#) that are similar to the ones on piston engines. If you've never seen the inside of a rotary engine, be prepared for a surprise, because you won't recognize much.

Rotor

The rotor has three convex faces, each of which acts like a piston. Each face of the rotor has a pocket in it, which increases the displacement of the engine, allowing more space



for air/fuel mixture.

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At the apex of each face is a metal blade that forms a seal to the outside of the combustion chamber. There are also metal rings on each side of the rotor that seal to the sides of the combustion chamber.

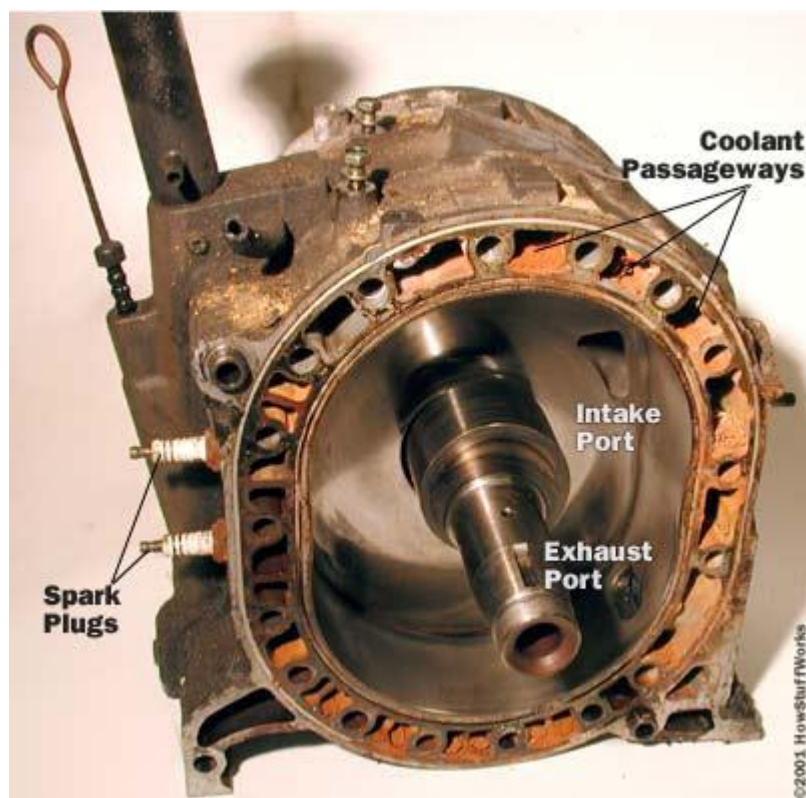
The rotor has a set of internal gear teeth cut into the center of one side. These teeth mate with a gear that is fixed to the housing. This gear mating determines the path and direction the rotor takes through the housing.

Housing

The housing is roughly oval in shape (its actually epitrochoid in shape -- check out this is a Java demonstration of [how the shape is derived](#)). The shape of the combustion chamber is designed so that the three tips of the rotor will always stay in contact with the wall of the chamber, forming three sealed volumes of gas.

Each part of the housing is dedicated to one part of the combustion process. The four sections are:

- **Intake**
- **Compression**
- **Combustion**
- **Exhaust**



The intake and exhaust ports are located in the housing. There are no valves in these ports. The exhaust port connects directly to the exhaust, and the intake port connects directly to the throttle.

Output

Shaft

The output shaft has round lobes mounted eccentrically, meaning that they are offset from the centerline of the shaft. Each rotor fits over one of these lobes. The lobe acts sort of like the crankshaft in a piston engine. As the rotor follows its path around the housing, it pushes on the lobes. Since the lobes are mounted eccentric to the output shaft, the force that the rotor applies to the lobes creates [torque](#) in the shaft, causing it to spin.



The output shaft -- note the eccentric lobes

Now let's take a look at how these parts are assembled.

Assembly of Rotary Engine

A rotary engine is assembled in layers. The two-rotor engine we took apart has five main layers that are held together by a ring of long bolts. [Coolant](#) flows through passageways surrounding all of the pieces.

The two end layers contain the seals and bearings for the output shaft. They also seal in the two sections of housing that contain the rotors. The inside surfaces of these pieces are very smooth, which helps the seals on the rotor do their job. An intake port is located on each of these end pieces.



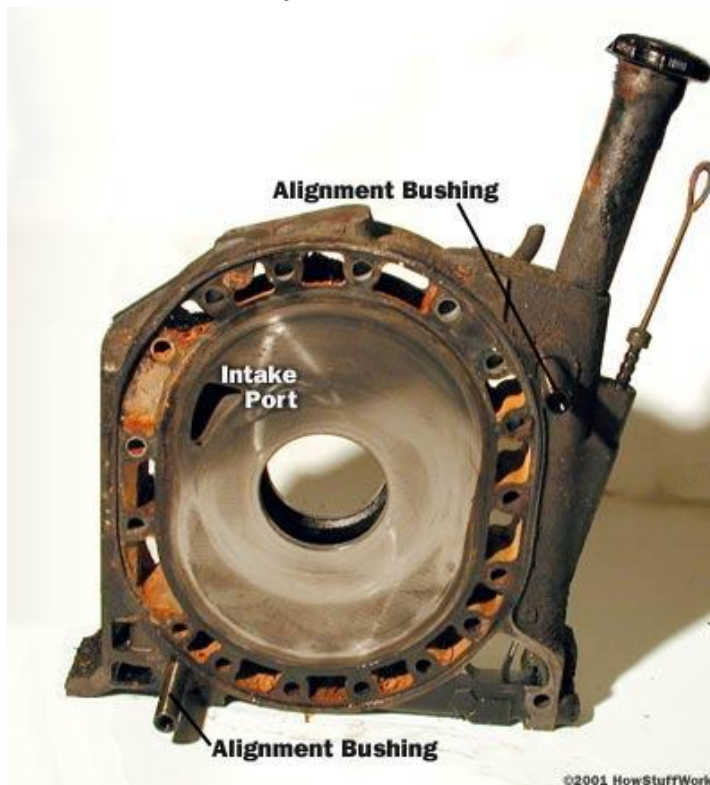
One of the two end pieces of a two-rotor Wankel engine

The next layer in from the outside is the oval-shaped rotor housing, which contains the exhaust ports. This is the part of the housing that contains the rotor.



The part of the rotor housing that holds the rotors -- note the exhaust port location

The center piece contains two intake ports, one for each rotor. It also separates the two rotors, so its outside surfaces are very smooth.



The center piece contains another intake port for each rotor.

In the center of each rotor is a large internal [gear](#) that rides around a smaller gear that is fixed to the housing of the engine. This is what determines the orbit of the rotor. The rotor also rides on the large circular lobe on the output shaft.

Next, we'll see how the engine actually makes power.

The Combustion Process

Rotary engines use the four-stroke combustion cycle, which is the same cycle that four-stroke piston engines use. But in a rotary engine, this is accomplished in a completely different way.

The heart of a rotary engine is the rotor. This is roughly the equivalent of the pistons in a piston engine. The rotor is mounted on a large circular lobe on the output shaft. This lobe is offset from the centerline of the shaft and acts like the crank handle on a winch, giving the rotor the leverage it needs to turn the output shaft. As the rotor orbits inside the housing, it pushes the lobe around in tight circles, turning **three times** for every one revolution of the rotor.

As the rotor moves through the housing, the three chambers created by the rotor change size. This size change produces a pumping action. Let's go through each of the four strokes of the engine looking at one face of the rotor.

Intake

The intake phase of the cycle starts when the tip of the rotor passes the intake port. At the moment when the intake port is exposed to the chamber, the volume of that chamber is close to its minimum. As the rotor moves past the intake port, the volume of the chamber expands, drawing air/fuel mixture into the chamber.

When the peak of the rotor passes the intake port, that chamber is sealed off and compression begins.

Compression

As the rotor continues its motion around the housing, the volume of the chamber gets smaller and the air/fuel mixture gets compressed. By the time the face of the rotor has made it around to the [spark plugs](#), the volume of the chamber is again close to its minimum. This is when combustion starts.

Combustion

Most rotary engines have two spark plugs. The shape of the combustion chamber is long, so the flame would spread too slowly if there were only one plug. When the spark plugs ignite the air/fuel mixture, pressure quickly builds, forcing the rotor to move.

The pressure of combustion forces the rotor to move in the direction that makes the chamber grow in volume. The combustion gases continue to expand, moving the rotor and creating power, until the peak of the rotor passes the exhaust port.

Exhaust

Once the peak of the rotor passes the exhaust port, the high-pressure combustion gases are free to flow out the exhaust. As the rotor continues to move, the chamber starts to contract, forcing the remaining exhaust out of the port. By the time the volume of the chamber is nearing its minimum, the peak of the rotor passes the intake port and the whole cycle starts again.

The neat thing about the rotary engine is that each of the three faces of the rotor is always working on one part of the cycle -- in one complete revolution of the rotor, there will be three combustion strokes. But remember, the output shaft spins three times for every

complete revolution of the rotor, which means that there is one combustion stroke for each revolution of the output shaft.

Differences between a rotary and a piston engine

There are several defining characteristics that differentiate a rotary engine from a typical piston engine.

Fewer Moving Parts

The rotary engine has far fewer moving parts than a comparable four-stroke piston engine. A two-rotor rotary engine has three main moving parts: the two rotors and the output shaft. Even the simplest four-cylinder piston engine has at least 40 moving parts, including pistons, connecting rods, [camshaft](#), valves, valve springs, rockers, timing belt, timing gears and crankshaft.

This minimization of moving parts can translate into better reliability from a rotary engine. This is why some aircraft manufacturers prefer rotary engines to piston engines.

Smoother

All the parts in a rotary engine spin continuously in one direction, rather than violently changing directions like the pistons in a conventional engine do. Rotary engines are internally balanced with spinning counterweights that are phased to cancel out any vibrations.

The power delivery in a rotary engine is also smoother. Because each combustion event lasts through 90-degrees of the rotor's rotation, and the output shaft spins three revolutions for each revolution of the rotor, each combustion event lasts through 270-degrees of the output shaft's rotation. This means that a single-rotor engine delivers power for three-quarters of each revolution of the output shaft. Compare this to a single-cylinder piston engine, in which combustion occurs during 180-degrees out of every **two** revolutions, or only a quarter of each revolution of the crankshaft (the output shaft of a piston engine).

Slower

Since the rotors spin at one-third the speed of the output shaft, the main moving parts of the engine move slower than the parts in a piston engine. This also helps with reliability.

Challenges

There are some challenges in designing a rotary engine:

- Typically, it is more difficult (but not impossible) to make a rotary engine meet U.S. emissions regulations.
- The manufacturing costs can be higher, mostly because the number of these engines produced is not as high as the number of piston engines.

They typically consume more fuel than a piston engine because the thermodynamic efficiency of the engine is reduced by the long combustion-chamber shape and low compression ratio.

Automotive Diesel Engines

Rudolf Diesel developed the idea for the diesel engine and obtained the German patent for it in 1892. His goal was to create an engine with **high efficiency**. Gasoline engines had been invented 1876 and, especially at that time, were not very efficient.

The main differences between the gasoline engine and the diesel engine are:

- A gasoline engine intakes a mixture of gas and air, compresses it and ignites the mixture with a spark. A diesel engine takes in just air, compresses it and then injects fuel into the compressed air. The heat of the compressed air lights the fuel spontaneously.
- A gasoline engine compresses at a ratio of 8:1 to 12:1, while a diesel engine compresses at a ratio of 14:1 to as high as 25:1. The higher compression ratio of the diesel engine leads to better efficiency.
- Gasoline engines generally use either [carburetion](#), in which the air and fuel is mixed long before the air enters the cylinder, or port [fuel injection](#), in which the fuel is injected just prior to the intake stroke (outside the cylinder). Diesel engines use direct fuel injection -- the diesel fuel is injected directly into the cylinder.

Note that the diesel engine has no spark plug, that it intakes air and compresses it, and that it then injects the fuel directly into the combustion chamber (direct injection). It is the heat of the compressed air that lights the fuel in a diesel engine.

In the simplified animation above, the green device attached to the left side of the cylinder is a **fuel injector**. However, the injector on a diesel engine is its most complex component and has been the subject of a great deal of experimentation -- in any particular engine it may be located in a variety of places. The injector has to be able to withstand the temperature and pressure inside the cylinder and still deliver the fuel in a fine mist. Getting the mist circulated in the cylinder so that it is evenly distributed is also a problem, so some diesel engines employ special induction valves, pre-combustion chambers or other devices to swirl the air in the combustion chamber or otherwise improve the ignition and combustion process.

One big difference between a diesel engine and a gas engine is in the injection process. Most car engines use port injection or a carburetor rather than direct injection. In a car engine, therefore, all of the fuel is loaded into the cylinder during the intake stroke and then compressed. The compression of the fuel/air mixture limits the compression ratio of the engine -- if it compresses the air too much, the fuel/air mixture spontaneously ignites and causes **knocking**. A diesel compresses only air, so the compression ratio can be much higher. The higher the compression ratio, the more power is generated.

Some diesel engines contain a **glow plug** of some sort. When a diesel engine is cold, the compression process may not raise the air to a high enough temperature to ignite the fuel. The glow plug is an electrically heated wire that helps ignite the fuel when the engine is cold so that the engine can start.

All functions in a modern engine are controlled by the ECM communicating with an elaborate set of sensors measuring everything from R.P.M. to engine coolant and oil temperatures and even engine position (i.e. T.D.C.). Glow plugs are rarely used today on larger engines. The ECM senses ambient air temperature and retards the timing of the

engine in cold weather so the injector sprays the fuel at a later time. The air in the cylinder is compressed more, creating more heat, which aids in starting. Smaller engines and engines that do not have such advanced [computer control](#) use glow plugs to solve the cold-starting problem.

Diesel Fuel

If you have ever compared diesel fuel and gasoline, you know that they are different. They certainly smell different. Diesel fuel is heavier and oilier. Diesel fuel evaporates much more slowly than gasoline -- its boiling point is actually higher than the boiling point of water. You will often hear diesel fuel referred to as "diesel oil" because it is so oily.

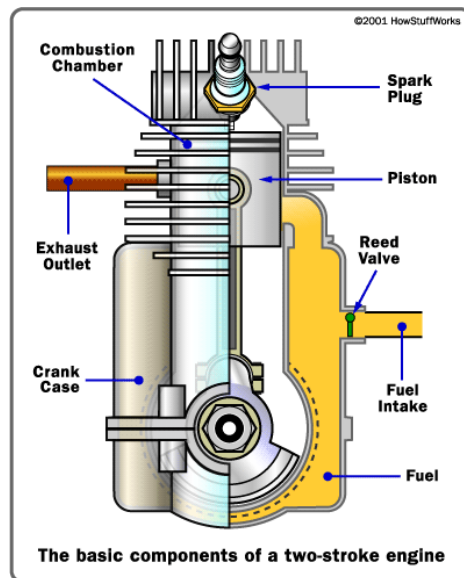
Diesel fuel evaporates more slowly because it is heavier. It contains more carbon atoms in longer chains than gasoline does (gasoline is typically C_9H_{20} , while diesel fuel is typically $C_{14}H_{30}$). It takes less [refining](#) to create diesel fuel, which is why it is generally cheaper than gasoline.

Diesel fuel has a **higher energy density** than gasoline. On average, 1 gallon (3.8 L) of diesel fuel contains approximately 155×10^6 joules (147,000 BTU), while 1 gallon of gasoline contains 132×10^6 joules (125,000 BTU). This, combined with the improved efficiency of diesel engines, explains why diesel engines get better mileage than equivalent gasoline engines.

Two-Stroke

- There is a third type of engine, known as a **two-stroke engine**, that is commonly found in lower-power applications.

Two-stroke Combustion process



This is what a two-stroke engine looks like:

You find two-stroke engines used in such devices as [chain saws](#) and jet skis because two-stroke engines have two important advantages over four-stroke engines:

- Two-stroke engines do not have valves, which simplifies their construction.
- Two-stroke engines fire once every revolution (four-stroke engines fire once every other revolution) -- this gives two-stroke engines a significant power boost.

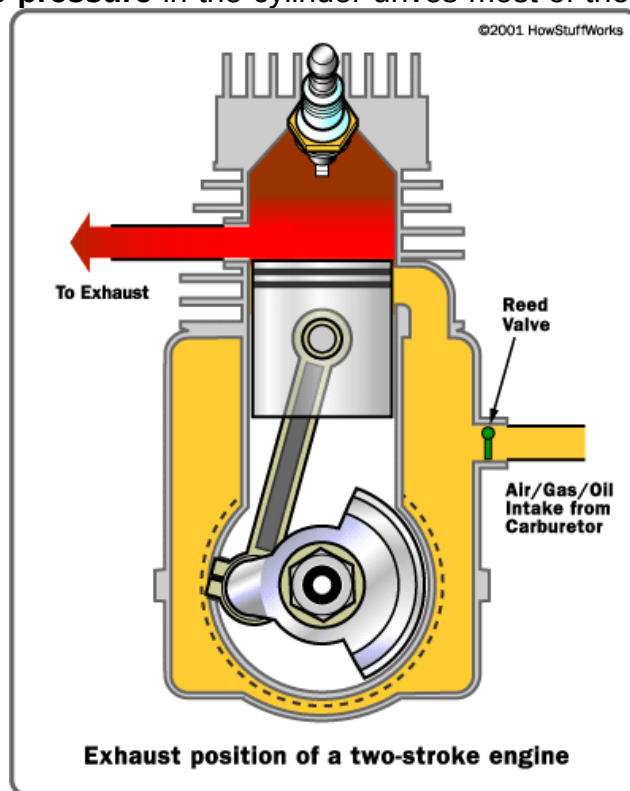
These two advantages make two-stroke engines **lighter**, simpler and less expensive to manufacture. They also have the potential to pack about **twice the power** into the same space because there are twice as many power strokes per revolution. The combination gives two-stroke engines a great **power-to-weight ratio**.

You don't see two-stroke engines in cars, however. That's because two-stroke engines have a couple of significant disadvantages that will make more sense once we look at the operation of a two-stroke engine.

The Two-stroke Cycle

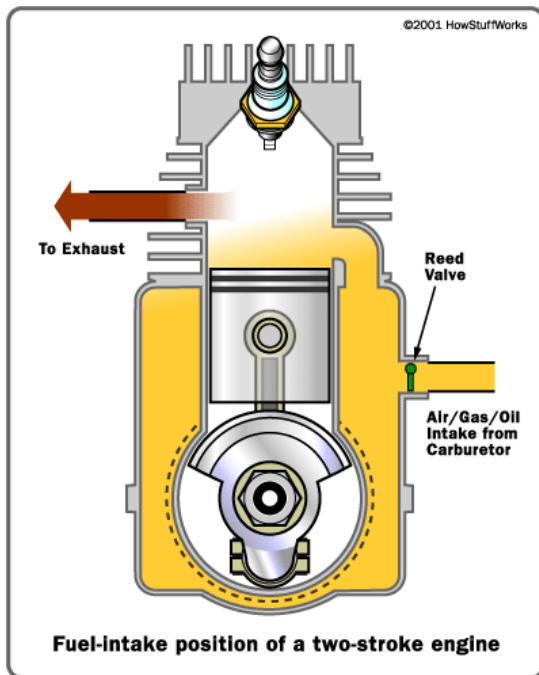
This figure shows a typical cross flow design. You can see that two-stroke engines are ingenious little devices that overlap operations in order to reduce the part count.

You can understand a two-stroke engine by watching each part of the cycle. Start with the point where the **spark plug** fires. Fuel and air in the cylinder have been compressed, and when the spark plug fires the mixture ignites. The resulting **explosion** drives the **piston** downward. Note that as the piston moves downward, it is compressing the air/fuel mixture in the crankcase. As the piston approaches the bottom of its stroke, the **exhaust port** is uncovered. The **pressure** in the cylinder drives most of the exhaust gases out of cylinder,



as shown here:

As the piston finally bottoms out, the **intake port** is uncovered. The piston's movement has **pressurized** the mixture in the crankcase, so it rushes into the cylinder, **displacing** the remaining exhaust gases and filling the cylinder with a fresh charge of fuel, as shown here:



Note that in many two-stroke engines that use a cross-flow design, the piston is shaped so that the incoming fuel mixture doesn't simply flow right over the top of the piston and out the exhaust port.

Now the momentum in the crankshaft starts driving the piston back toward the spark plug for the **compression stroke**. As the air/fuel mixture in the piston is compressed, a **vacuum** is created in the crankcase. This vacuum opens the **reed valve** and sucks air/fuel/oil in from the **carburetor**.

Once the piston makes it to the end of the compression stroke, the spark plug fires again to repeat the cycle. It's called a two-stroke engine because there is a **compression stroke** and then a **combustion stroke**. In a four-stroke engine, there are separate intake, compression, combustion and exhaust strokes.

You can see that the piston is really doing three different things in a two-stroke engine:

- On one side of the piston is the **combustion chamber**, where the piston is compressing the air/fuel mixture and capturing the energy released by the ignition of the fuel.
- On the other side of the piston is the **crankcase**, where the piston is creating a vacuum to suck in air/fuel from the carburetor through the reed valve and then pressurizing the crankcase so that air/fuel is forced into the combustion chamber.
- Meanwhile, the sides of the piston are acting like **valves**, covering and uncovering the intake and exhaust ports drilled into the side of the cylinder wall.

It's really pretty neat to see the piston doing so many different things! That's what makes two-stroke engines so simple and lightweight.

If you have ever used a two-stroke engine, you know that you have to mix special **two-stroke oil** in with the gasoline. Now that you understand the two-stroke cycle you can see why. In a four-stroke engine, the crankcase is completely separate from the combustion chamber, so you can fill the crankcase with heavy oil to lubricate the crankshaft bearings, the bearings on either end of the piston's connecting rod and the cylinder wall. In a two-stroke engine, on the other hand, the crankcase is serving as a **pressurization chamber** to force air/fuel into the cylinder, so it can't hold a thick oil. Instead, you mix oil in with the

gas to lubricate the crankshaft, connecting rod and cylinder walls. If you forget to mix in the oil, the engine isn't going to last very long!

Disadvantages of the Two-stroke Engine

You can now see that two-stroke engines have two important advantages over four-stroke engines: They are simpler and lighter, and they produce about twice as much power. So why do all cars and trucks use four-stroke engines? There are four reasons:

- Two-stroke engines don't last nearly as long as four-stroke engines. The lack of a dedicated lubrication system means that the parts of a two-stroke engine wear a lot faster.
- Two-stroke oil is expensive, and you need about 4 ounces of it per gallon of gas. You would burn about a gallon of oil every 1,000 miles if you used a two-stroke engine in a car.
- Two-stroke engines do not use fuel efficiently, so you would get fewer miles per gallon.
- Two-stroke engines produce a lot of pollution. So much, in fact, that it is likely that you won't see them around too much longer.

The **pollution** comes from two sources. The first is the combustion of the oil. The oil makes all two-stroke engines smoky to some extent, and a badly worn two-stroke engine can emit huge clouds of oily smoke.

Each time a new charge of air/fuel is loaded into the combustion chamber, part of it **leaks out** through the exhaust port. That's why you see a sheen of oil around any two-stroke boat motor. The leaking hydrocarbons from the fresh fuel combined with the leaking oil is a real mess for the environment. These disadvantages mean that two-stroke engines are used only in applications where the motor is not used very often and the fantastic power-to-weight ratio of the two-stroke engine is important.

Meantime, manufacturers have been working to shrink and lighten four-stroke engines, and you can see that research coming to market in a variety of new marine and lawn-care products.

Gas Turbine

Most commercial jets are powered by turbofan engines, and turbofans are one example of a general class of engines called **gas turbine** engines. They are used in all kinds of unexpected places. For example, many of the [helicopters](#) you see, a lot of smaller [power plants](#) and even the [M-1 Tank](#) use gas turbines.

In a gas turbine, a pressurized gas spins the turbine. In all modern gas turbine engines, the engine produces its own pressurized gas, and it does this by burning something like propane, natural gas, kerosene or jet fuel. The heat that comes from burning the fuel expands air, and the high-speed rush of this hot air spins the turbine.

Advantages and Disadvantages

So why does the M-1 tank use a 1,500 [horsepower](#) gas turbine engine instead of a [diesel engine](#)? It turns out that there are two big advantages of the turbine over the diesel:

- Gas turbine engines have a great **power-to-weight ratio** compared to [reciprocating engines](#). That is, the amount of power you get out of the engine compared to the weight of the engine itself is very good.
- Gas turbine engines are **smaller** than their reciprocating counterparts of the same power.

The main disadvantage of gas turbines is that, compared to a reciprocating engine of the same size, they are **expensive**. Because they spin at such high speeds and because of the high operating temperatures, designing and manufacturing gas turbines is a tough problem from both the engineering and materials standpoint. Gas turbines also tend to use more fuel when they are idling, and they prefer a constant rather than a fluctuating load. That makes gas turbines great for things like transcontinental jet aircraft and power plants, but explains why you don't have one under the bonnet of your car yet.

The Gas Turbine Process

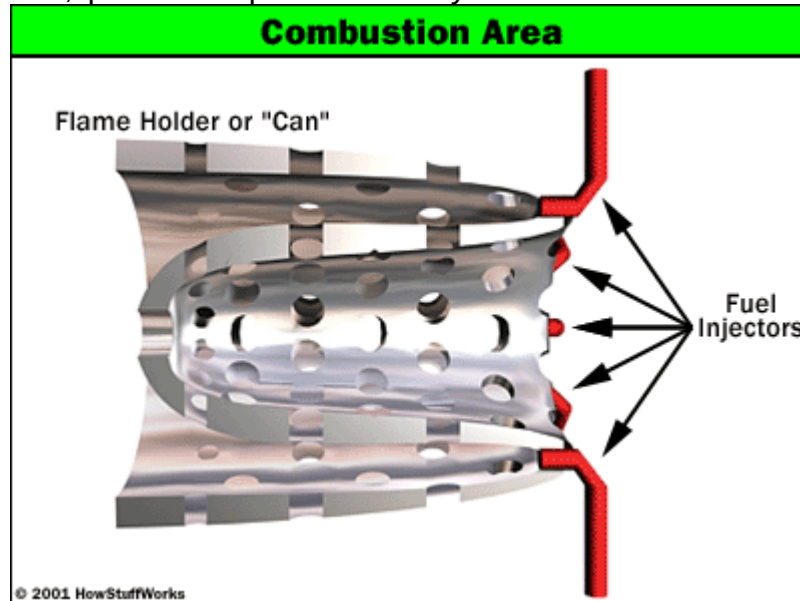
Gas turbine engines are, theoretically, extremely simple. They have three parts:

- **Compressor** - Compresses the incoming air to high pressure
- **Combustion area** - Burns the fuel and produces high-pressure, high-velocity gas
- **Turbine** - Extracts the energy from the high-pressure, high-velocity gas flowing from the combustion chamber

In this engine, air is sucked in from the right by the compressor. The compressor is basically a cone-shaped cylinder with small fan blades attached in rows. Assuming the light blue represents air at normal air pressure, then as the air is forced through the compression stage its pressure rises significantly. In some engines, the pressure of the air can rise by a factor of 30. The high-pressure air produced by the compressor is shown in dark blue.

This high-pressure air then enters the combustion area, where a ring of [fuel injectors](#) injects a steady stream of fuel. The fuel is generally kerosene, jet fuel, propane or natural gas. If you think about how easy it is to blow a candle out, then you can see the design problem in the combustion area -- entering this area is high-pressure air moving at hundreds of miles per hour. You want to keep a flame burning continuously in that environment. The piece that solves this problem is called a "flame holder," or sometimes a

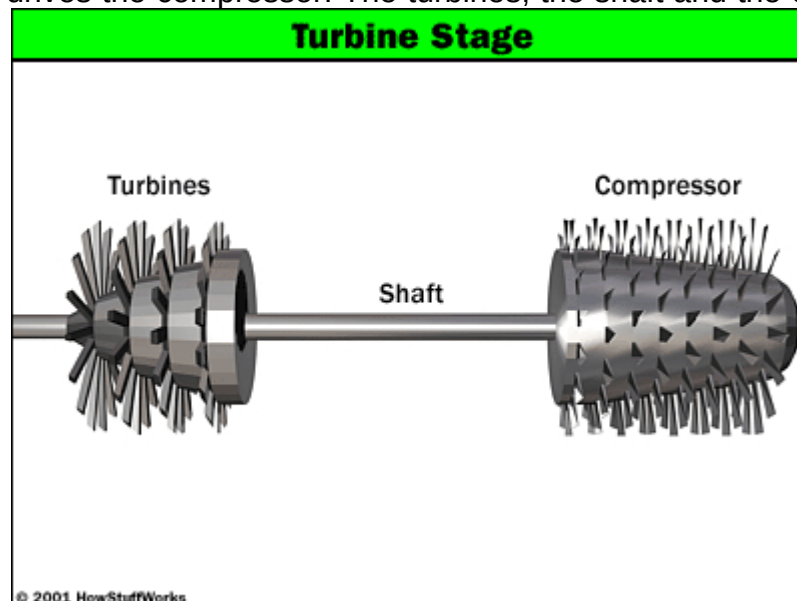
"can." The **can** is a hollow, perforated piece of heavy metal. Half of the can in cross-



section is shown below:

The **injectors** are at the right. Compressed air enters through the perforations. Exhaust gases exit at the left. You can see in the previous figure that a **second set of cylinders** wraps around the inside and the outside of this perforated can, guiding the compressed intake air into the perforations.

At the left of the engine is the **turbine** section. In this figure there are two sets of turbines. The first set directly drives the compressor. The turbines, the shaft and the compressor all



turn as a single unit:

At the far left is a final turbine stage, shown here with a single set of vanes. It drives the output shaft. This final turbine stage and the output shaft are a completely stand-alone, freewheeling unit. They spin freely without any connection to the rest of the engine. And that is the amazing part about a gas turbine engine -- there is enough energy in the hot gases blowing through the blades of that final output turbine to generate 1,500 horsepower and drive a 63-ton [M-1 Tank](#)! A gas turbine engine really is that simple.

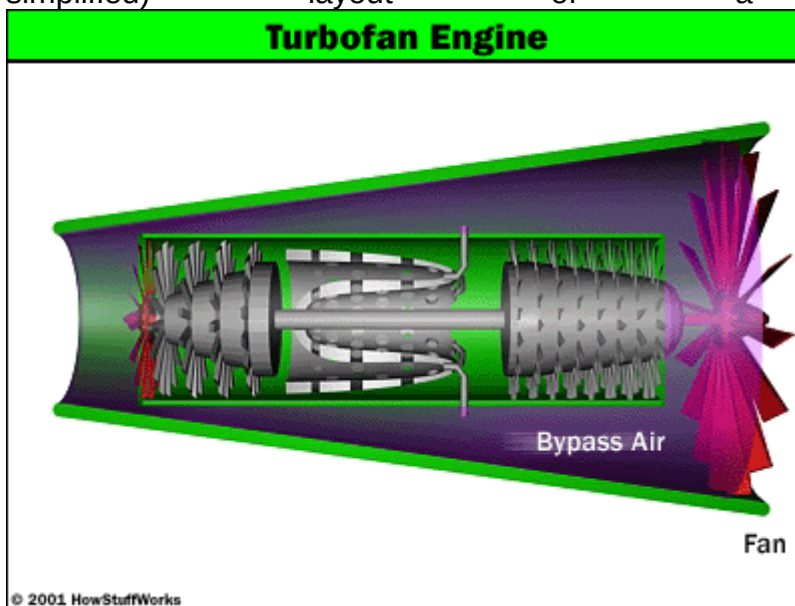
In the case of the turbine used in a tank or a [power plant](#), there really is nothing to do with the exhaust gases but vent them through an exhaust pipe. Sometimes the exhaust will run

through some sort of heat exchanger either to extract the heat for some other purpose or to preheat air before it enters the combustion chamber.

The discussion here is obviously simplified a bit. For example, we have not discussed the areas of [bearings](#), oiling systems, internal support structures of the engine, stator vanes and so on. All of these areas become major engineering problems because of the tremendous temperatures, pressures and spin rates inside the engine. But the basic principles described here govern all gas turbine engines and help you to understand the basic layout and operation of the engine.

Other Variations

Large jetliners use what are known as **turbofan** engines, which are nothing more than gas turbines combined with a large fan at the front of the engine. Here's the basic (highly simplified) layout of a turbofan engine:



You can see that the core of a turbofan is a normal gas turbine engine like the one described in the previous section. The difference is that the final turbine stage drives a shaft that makes its way back to the front of the engine to power the **fan** (shown in red in this picture). This **multiple concentric shaft approach**, by the way, is extremely common in gas turbines. In many larger turbofans, in fact, there may be two completely separate compression stages driven by separate turbines, along with the fan turbine as shown above. All three shafts ride within one another concentrically.

The purpose of the fan is to dramatically increase the amount of air moving through the engine, and therefore increase the engine's **thrust**. When you look into the engine of a commercial jet at the [airport](#), what you see is this fan at the front of the engine. It is huge -- on the order of 10 feet (3 m) in diameter on big jets, so it can move a lot of air. The air that the fan moves is called "**bypass air**" (shown in purple above) because it bypasses the turbine portion of the engine and moves straight through to the back of the nacelle at high speed to provide thrust.

A **turboprop** engine is similar to a turbofan, but instead of a fan there is a conventional **propeller** at the front of the engine. The output shaft connects to a **gearbox** to reduce the speed, and the output of the [gearbox](#) turns the propeller.

Jet Engine Thrust

The goal of a turbofan engine is to produce **thrust** to drive the [airplane](#) forward. Thrust is generally measured in pounds in the United States (the metric system uses Newtons, where 4.45 Newtons equals 1 pound of thrust). A "pound of thrust" is equal to a force able to accelerate 1 pound of material 32 feet per second per second (32 feet per second per second happens to be equivalent to the acceleration provided by [gravity](#)). Therefore, if you have a jet engine capable of producing 1 pound of thrust, it could hold 1 pound of material suspended in the air if the jet were pointed straight down. Likewise, a jet engine producing 5,000 pounds of thrust could hold 5,000 pounds of material suspended in the air. And if a rocket engine produced 5,000 pounds of thrust applied to a 5,000-pound object floating in space, the 5,000-pound object would accelerate at a rate of 32 feet per second per second.

Thrust is generated under Newton's principle that "every action has an equal and opposite reaction." For example, imagine that you are floating in space and you weigh 100 pounds on Earth. In your hand you have a baseball that weighs 1 pound on Earth. If you throw the baseball away from you at a speed of 32 feet per second (21 mph / 34 kph), your body will move in the opposite direction (it will **react**) at a speed of 0.32 feet per second. If you were to continuously throw baseballs in that way at a rate of one per second, your baseballs would be generating 1 pound of continuous thrust. Keep in mind that to generate that 1 pound of thrust for an hour you would need to be holding 3,600 pounds of baseballs at the beginning of the hour. If you wanted to do better, the thing to do is to throw the baseballs harder. By "throwing" them (with of a gun, say) at 3,200 feet per second, you would generate 100 pounds of thrust.

In a turbofan engine, the baseballs that the engine is throwing out are **air molecules**. The air molecules are already there, so the airplane does not have to carry them around at least. An individual air molecule does not weigh very much, but the engine is throwing a lot of them and it is throwing them at very high speed. Thrust is coming from two components in the turbofan:

- The **gas turbine** itself - Generally a nozzle is formed at the exhaust end of the gas turbine (not shown in this figure) to generate a high-speed jet of exhaust gas. A typical speed for air molecules exiting the engine is 1,300 mph (2,092 kph).
- The **bypass air** generated by the fan - This bypass air moves at a slower speed than the exhaust from the turbine, but the fan moves a lot of air.

Increasing Engine Power for Petrol Engines

Increase displacement -- More displacement means more power because you can burn more gas during each revolution of the engine. You can increase displacement by making the cylinders bigger or by adding more cylinders. Twelve cylinders seems to be the practical limit.

Increase the compression ratio -- Higher compression ratios produce more power, up to a point. The more you compress the air/fuel mixture, however, the more likely it is to spontaneously burst into flame (before the spark plug ignites it). Higher octane gasolines prevent this sort of early combustion. That is why high-performance cars generally need

high octane gasoline -- their engines are using higher compression ratios to get more power.

Stuff more into each cylinder -- If you can cram more air (and therefore fuel) into a cylinder of a given size, you can get more power from the cylinder (in the same way that you would by increasing the size of the cylinder). Turbo chargers and super chargers pressurize the incoming air to effectively cram more air into a cylinder.

Cool the incoming air -- Compressing air raises its temperature. However, you would like to have the coolest air possible in the cylinder because the hotter the air is, the less it will expand when combustion takes place. Therefore, many turbo charged and super charged cars have an **intercooler**. An intercooler is a special radiator through which the compressed air passes to cool it off before it enters the cylinder.

Let air come in more easily -- As a piston moves down in the intake stroke, air resistance can rob power from the engine. Air resistance can be lessened dramatically by putting two intake valves in each cylinder. Some newer cars are also using polished intake manifolds to eliminate air resistance there. Bigger air filters can also improve air flow.

Let exhaust exit more easily -- If air resistance makes it hard for exhaust to exit a cylinder, it robs the engine of power. Air resistance can be lessened by adding a second exhaust valve to each cylinder (a car with two intake and two exhaust valves has four valves per cylinder, which improves performance -- when you hear a car ad tell you the car has four cylinders and 16 valves, what the ad is saying is that the engine has four valves per cylinder). If the exhaust pipe is too small or the muffler has a lot of air resistance, this can cause back-pressure, which has the same effect. High-performance exhaust systems use headers, big tail pipes and free-flowing mufflers to eliminate back-pressure in the exhaust system. When you hear that a car has "dual exhaust," the goal is to improve the flow of exhaust by having two exhaust pipes instead of one.

Make everything lighter -- Lightweight parts help the engine perform better. Each time a piston changes direction, it uses up energy to stop the travel in one direction and start it in another. The lighter the piston, the less energy it takes.

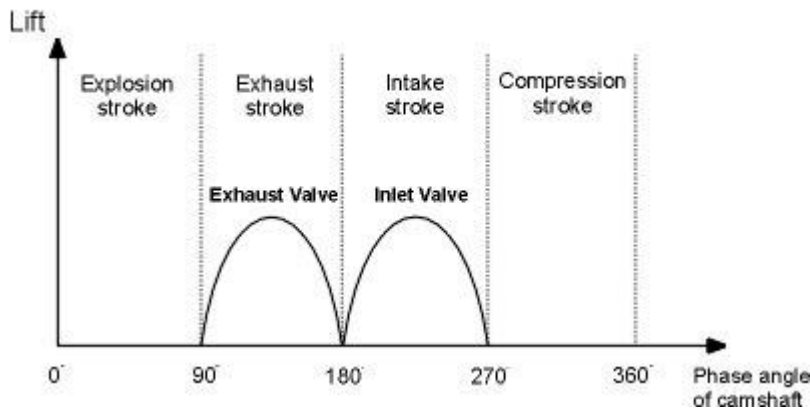
Inject the fuel -- Fuel injection allows very precise metering of fuel to each cylinder. This improves performance and fuel economy.

Variable Valve Timing (VVT)

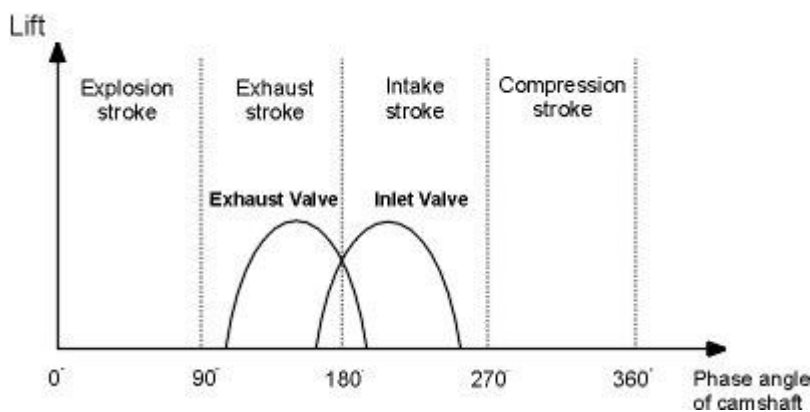
After multi-valve technology became standard in engine design, Variable Valve Timing becomes the next step to enhance engine output, no matter power or torque.

As you know, valves activate the breathing of engine. The timing of breathing, that is, the timing of air intake and exhaust, is controlled by the shape and phase angle of cams. To optimise the breathing, engine requires different valve timing at different speed. When the rev increases, the duration of intake and exhaust stroke decreases so that fresh air becomes not fast enough to enter the combustion chamber, while the exhaust becomes not fast enough to leave the combustion chamber. Therefore, the best solution is to open the inlet valves earlier and close the exhaust valves later. In other words, the **Overlapping** between intake period and exhaust period should be increased as rev increases.

Normal valve timing



High Speed - BMW Double VANOS



Without Variable Valve Timing technology, engineers used to choose the best compromise timing. For example, a van may adopt less overlapping for the benefits of low speed output. A racing engine may adopt considerable overlapping for high speed power. An ordinary sedan may adopt valve timing optimised for mid-rev so that both the low speed drivability and high speed output will not be sacrificed too much. No matter which one, the result is just optimised for a particular speed.

With Variable Valve Timing, power and torque can be optimised across a wide rpm band. The most noticeable results are:

- The engine can rev higher, thus raises peak power. For example, Nissan's 2-litre Neo VVL engine output 25% more peak power than its non-VVT version.
- Low-speed torque increases, thus improves drivability. For example, Fiat Barchetta's 1.8 VVT engine provides 90% peak torque between 2,000 and 6,000 rpm.

Moreover, all these benefits come without any drawback.

Variable Lift

In some designs, valve lift can also be varied according to engine speed. At high speed, higher lift quickens air intake and exhaust, thus further optimise the breathing. Of course, at lower speed such lift will generate counter effects like deteriorating the mixing process of fuel and air, thus decrease output or even leads to misfire. Therefore the lift should be variable according to engine speed.

Different Types of VVT

1) Cam-Changing VVT

Honda pioneered road car-used VVT in the late 80s by launching its famous VTEC system (Valve Timing Electronic Control). First appeared in Civic, CRX and NS-X, then became standard in most models.

You can see it as 2 sets of cams having different shapes to enable different timing and lift. One set operates during normal speed, say, below 4,500 rpm. Another substitutes at higher speed. Obviously, such layout does not allow continuous change of timing, therefore the engine performs modestly below 4,500 rpm but above that it will suddenly transform into a wild animal.

This system does improve peak power - it can raise red line to nearly 8,000 rpm (even 9,000 rpm in S2000), just like an engine with racing camshafts, and increase top end power by as much as 30 hp for a 1.6-litre engine !! However, to exploit such power gain, you need to keep the engine boiling at above the threshold rpm, therefore frequent gear change is required. As low-speed torque gains too little (remember, the cams of a normal engine usually serves across 0-6,000 rpm, while the "slow cams" of VTEC engine still need to serve across 0-4,500 rpm), drivability won't be too impressive. In short, cam-changing system is best suited to sports cars.

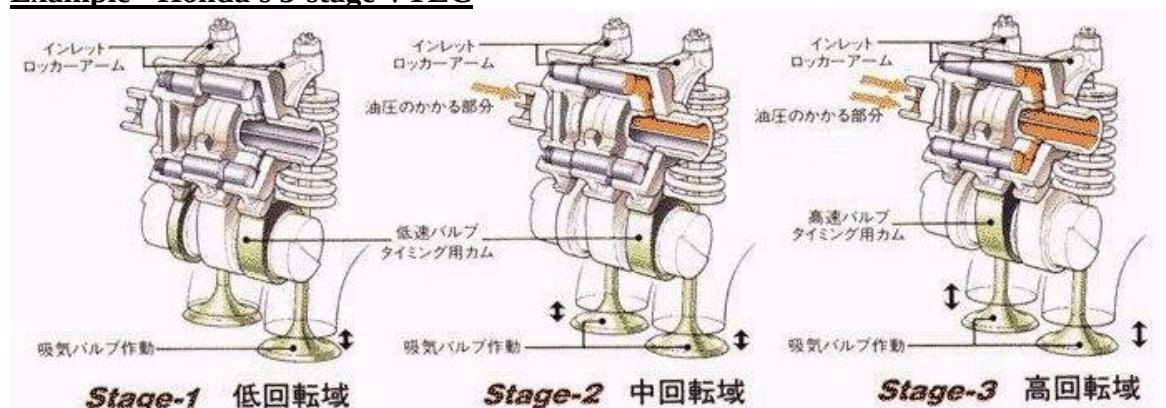
Honda has already improved its 2-stage VTEC into 3 stages for some models. Of course, the more stage it has, the more refined it becomes. It still offers less broad spread of torque as other continuously variable systems. However, cam-changing system remains to be the most powerful VVT, since no other system can vary the **Lift** of valve as it does.

Advantage: Powerful at top end

Disadvantage: 2 or 3 stages only, non-continuous; no much improvement to torque; complex

Who use it ? Honda VTEC, Mitsubishi MIVEC, Nissan Neo VVL.

Example - Honda's 3-stage VTEC



Honda's latest 3-stage VTEC has been applied in Civic sohc engine in Japan. The mechanism has 3 cams with different timing and lift profile. Note that their dimensions are also different - the middle cam (fast timing, high lift), as shown in the above diagram, is the

largest; the right hand side cam (slow timing, medium lift) is medium sized ; the left hand side cam (slow timing, low lift) is the smallest.

This mechanism operate like this :

Stage 1 (low speed) : the 3 pieces of rocker arms moves independently. Therefore the left rocker arm, which actuates the left inlet valve, is driven by the low-lift left cam. The right rocker arm, which actuates the right inlet valve, is driven by the medium-lift right cam. Both cams' timing is relatively slow compare with the middle cam, which actuates no valve now.

Stage 2 (medium speed) : hydraulic pressure (painted orange in the picture) connects the left and right rocker arms together, leaving the middle rocker arm and cam to run on their own. Since the right cam is larger than the left cam, those connected rocker arms are actually driven by the right cam. As a result, both inlet valves obtain slow timing but medium lift.

Stage 3 (high speed) : hydraulic pressure connects all 3 rocker arms together. Since the middle cam is the largest, both inlet valves are actually driven by that fast cam. Therefore, fast timing and high lift are obtained in both valves.

Another example - Nissan Neo VVL

Very similar to Honda's system, but the right and left cams are with the same profile. At low speed, both rocker arms are driven independently by those slow-timing, low-lift right and left cams. At high speed, 3 rocker arms are connected together such that they are driven by the fast-timing, high-lift middle cam.

You might think it must be a 2-stage system. No, it is not. Since Nissan Neo VVL duplicates the same mechanism in the exhaust camshaft, 3 stages could be obtained in the following way:

Stage 1 (low speed) : both intake and exhaust valves are in slow configuration.

Stage 2 (medium speed) : fast intake configuration + slow exhaust configuration.

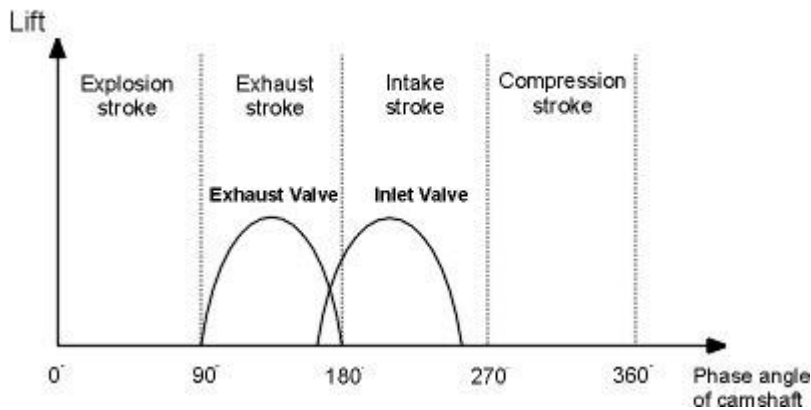
Stage 3 (high speed) : both intake and exhaust valves are in fast configuration.

2) Cam-Phasing VVT

Cam-phasing VVT is the simplest, cheapest and most commonly used mechanism at this moment. However, its performance gain is also the least, very fair indeed.

Basically, it varies the valve timing by shifting the phase angle of camshafts. For example, at high speed, the inlet camshaft will be rotated in advance by 30° so to enable earlier intake. This movement is controlled by engine management system according to need, and actuated by hydraulic valve gears. Note that cam-phasing VVT cannot vary the duration of valve opening. It just allows earlier or later valve opening. Earlier open results in earlier close, of course. It also cannot vary the valve lift, unlike cam-changing VVT. However, cam-phasing VVT is the simplest and cheapest form of VVT because each camshaft needs only one hydraulic phasing actuator, unlike other systems that employ individual mechanism for every cylinder.

High Speed - Toyota VVT-i



Continuous or Discrete

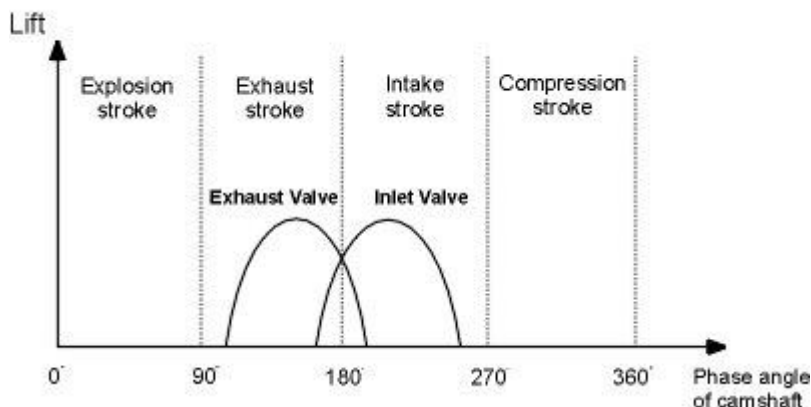
Simpler cam-phasing VVT has just 2 or 3 fixed shift angle settings to choose from, such as either 0° or 30°. Better system has continuous variable shifting, say, any arbitrary value between 0° and 30°, depends on rpm. Obviously this provide the most suitable valve timing at any speed, thus greatly enhance engine flexibility. Moreover, the transition is so smooth that hardly noticeable.

Intake and Exhaust

Some design, such as BMW's Double Vanos system, has cam-phasing VVT at both intake and exhaust camshafts, this enable more overlapping, hence higher efficiency. This explain why BMW M3 3.2 (100hp/litre) is more efficient than its predecessor, M3 3.0 (95hp/litre) whose VVT is bounded at the inlet valves.

In the E46 3-series, the Double Vanos shift the intake camshaft within a maximum range of 40°. The exhaust camshaft is 25°.

High Speed - BMW Double VANOS



Advantage: Cheap and simple, continuous VVT improves torque delivery across the whole rev range.

Disadvantage: Lack of variable lift and variable valve opening duration, thus less top end power than cam-changing VVT.

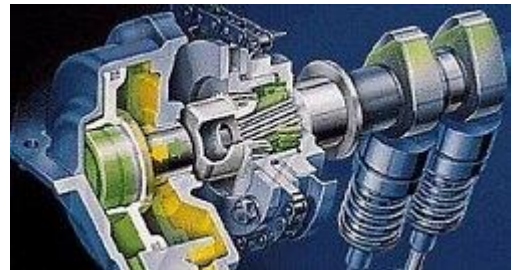
Who use it ? Most car makers, such as:

- Audi 2.0-litre - continous inlet
- Audi 3.0 V6 - continous inlet, 2-stage exhaust
- Audi V8 - inlet, 2-stage discrete

- BMW Double Vanos - inlet and exhaust, continuous
- Ferrari 360 Modena - exhaust, 2-stage discrete
- Fiat (Alfa) SUPER FIRE - inlet, 2-stage discrete
- Ford Puma 1.7 Zetec SE - inlet, 2-stage discrete
- Ford Falcon XR6's VCT - inlet, 2-stage discrete
- Jaguar AJ-V6 and updated AJ-V8 - inlet, continuous
- Lamborghini Diablo V12 since SV - inlet, 2-stage discrete
- Mazda MX-5's S-VT - continuous inlet
- Mercedes V6 and V8 - inlet, 2-stage ?
- Nissan QR four-pot and V8 - continuous inlet
- Nissan VQ V6 - inlet, continuous ?
- Nissan VQ V6 since Skyline V35 - inlet, electromagnetic
- Porsche Variocam - inlet, 3-stage discrete
- PSA / Renault 3.0 V6 - inlet, 2-stage
- Renault 2.0-litre - inlet, 2-stage discrete
- Subaru AVCS - inlet, 2-stage ?
- Toyota VVT-i - continuous, mostly inlet but some also exhaust
- Volvo 4 / 5 / 6-cylinder modular engines - inlet, continuous
- Volkswagen VR6 - inlet, continuous ?
- Volkswagen (Audi) W8 and W12 - continuous inlet, 2-stage exhaust

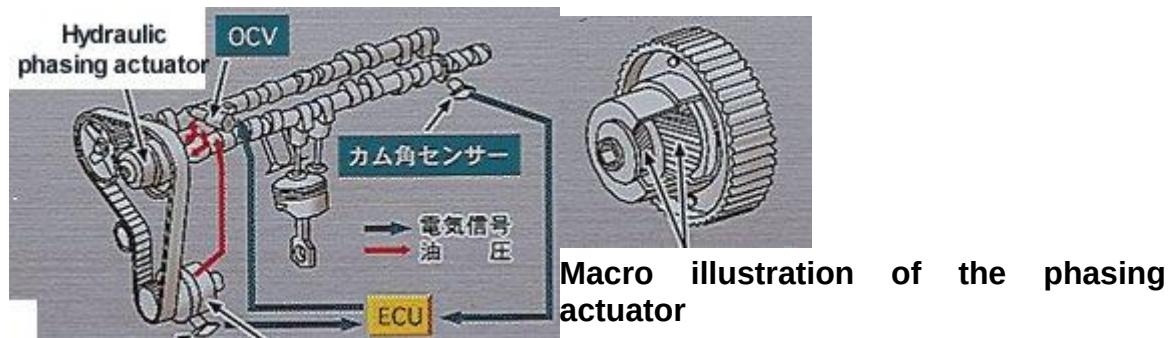
Example : BMW's Vanos

From the picture, it is easy to understand its operation. The end of camshaft incorporates a gear thread. The thread is coupled by a cap which can move towards and away from the camshaft. Because the gear thread is not in parallel to the axis of camshaft, phase angle will shift forward if the cap is pushed towards the camshaft. Similarly, pulling the cap away from the camshaft results in shifting the phase angle backward.



Whether push or pull is determined by the hydraulic pressure. There are 2 chambers right beside the cap and they are filled with liquid (these chambers are colored green and yellow respectively in the picture) A thin piston separates these 2 chambers, the former attaches rigidly to the cap. Liquid enter the chambers via electromagnetic valves which controls the hydraulic pressure acting on which chambers. For instance, if the engine management system signals the valve at the green chamber open, then hydraulic pressure acts on the thin piston and push the latter, accompany with the cap, towards the camshaft, thus shift the phase angle forward. Continuous variation in timing is easily implemented by positioning the cap at a suitable distance according to engine speed.

Another Example : Toyota VVT-i



Toyota's VVT-i (Variable Valve Timing - Intelligent) has been spreading to more and more of its models, from the tiny Yaris (Vitz) to the Supra. Its mechanism is more or less the same as BMW's Vanos, it is also a continuously variable design. However, the word "Intelligent" emphasizes the clever control program. Not only varies timing according to engine speed, it also considers other conditions such as acceleration, going up hill or down hill.

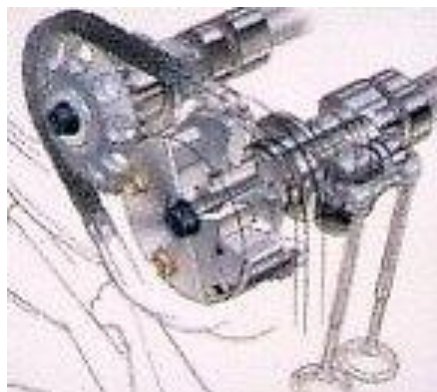
3) Cam-Changing + Cam-Phasing VVT

Combining cam-changing VVT and cam-phasing VVT could satisfy the requirement of both top-end power and flexibility throughout the whole rev range, but it is inevitably more complex. At the time of writing, only Toyota and Porsche have such designs. However, I believe in the future more and more sports cars will adopt this kind of VVT.

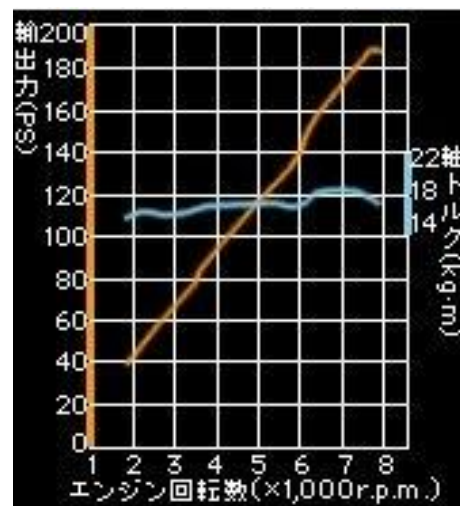
Example: Toyota VVTL-i

Toyota's VVTL-i is the most sophisticated VVT design yet. Its powerful functions include:

- Continuous cam-phasing variable valve timing
- 2-stage variable valve lift plus valve-opening duration
 - Applied to both intake and



exhaust valves

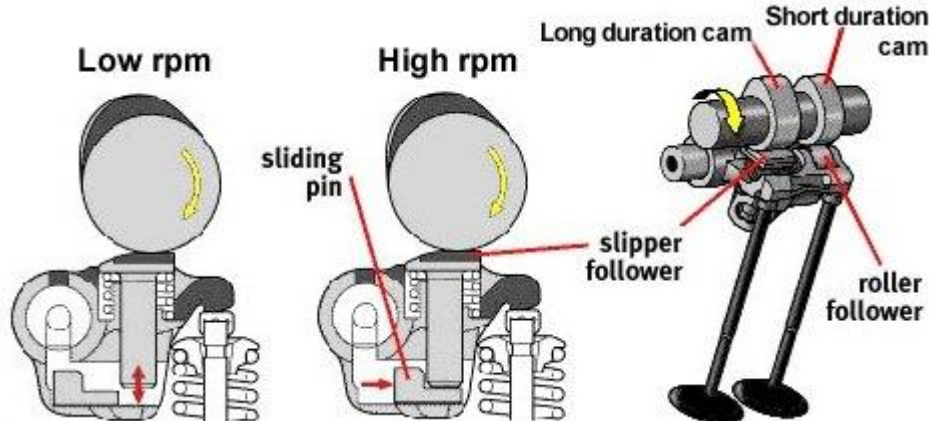


The system could be seen as a combination of existing VVT-i and Honda's VTEC, although the mechanism for the variable lift is different from Honda.

Like VVT-i, the variable valve timing is implemented by shifting the phase angle of the whole camshaft forward or reverse by means of a hydraulic actuator attached to the end of

the camshaft. The timing is calculated by the engine management system with engine speed, acceleration, going up hill or down hill etc. taking into consideration. Moreover, the variation is continuous across a wide range of up to 60°, therefore the variable timing alone is perhaps the most perfect design up to now.

What makes the VVTL-i superior to the ordinary VVT-i is the "L", which stands for Lift (valve lift) as everybody knows. Let's see the following illustration:



Like VTEC, Toyota's system uses a single rocker arm follower to actuate both intake valves (or exhaust valves). It also has 2 cam lobes acting on that rocker arm follower, the lobes have different profile - one with longer valve-opening duration profile (for high speed), another with shorter valve-opening duration profile (for low speed). At low speed, the slow cam actuates the rocker arm follower via a roller bearing (to reduce friction). The high speed cam does not have any effect to the rocker follower because there is sufficient spacing underneath its hydraulic tappet.

A flat torque output (blue curve)

When speed has increased to the threshold point, the sliding pin is pushed by hydraulic pressure to fill the spacing. The high speed cam becomes effective. Note that the fast cam provides a longer valve-opening duration while the sliding pin adds valve lift. (for Honda VTEC, both the duration and lift are implemented by the cam lobes)

Obviously, the variable valve-opening duration is a 2-stage design, unlike Rover VVC's continuous design. However, VVTL-i offers variable lift, which lifts its high speed power output a lot. Compare with Honda VTEC and similar designs for Mitsubishi and Nissan, Toyota's system has continuously variable valve timing which helps it to achieve far better low to medium speed flexibility. Therefore it is undoubtedly the best VVT today. However, it is also more complex and probably more expensive to build.

Advantage: Continuous VVT improves torque delivery across the whole rev range; Variable lift and duration lift high rev power.

Disadvantage: More complex and expensive

Who use it ? Toyota 1.8-litre 190hp for Celica GT-S and hot Corolla

Example 2: Porsche Variocam Plus



Variocam Plus uses hydraulic phasing actuator and variable tappets



Variocam of the 911 Carrera uses timing chain for cam phasing.

Porsche's Variocam Plus was said to be developed from the Variocam which serves the Carrera and Boxster. However, I found their mechanisms virtually share nothing. The Variocam was first introduced to the 968 in 1991. It used timing chain to vary the phase angle of camshaft, thus provided 3-stage variable valve timing. 996 Carrera and Boxster also use the same system. This design is unique and patented, but it is actually inferior to the hydraulic actuator favoured by other car makers, especially it doesn't allow as much variation to phase angle.

Therefore, the Variocam Plus used in the new 911 Turbo finally follow uses the popular hydraulic actuator instead of chain. One well-known Porsche expert described the variable valve timing as continuous, but it seems conflicting with the official statement made earlier, which revealed the system has 2-stage valve timing.

However, the most influential changes of the "Plus" is the addition of variable valve lift. It is implemented by using variable hydraulic tappets. As shown in the picture, each valve is served by 3 cam lobes - the center one has obviously less lift (3 mm only) and shorter duration for valve opening. In other words, it is the "slow" cam. The outer two cam lobes are exactly the same, with fast timing and high lift (10 mm). Selection of cam lobes is made by the variable tappet, which actually consists of an inner tappet and an outer (ring-shape) tappet. They could be locked together by a hydraulic-operated pin passing through them. In this way, the "fast" cam lobes actuate the valve, providing high lift and long duration opening. If the tappets are not locked together, the valve will be actuated by the "slow" cam lobe via the inner tappet. The outer tappet will move independent of the valve lifter.

As seen, the variable lift mechanism is unusually simple and space-saving. The variable tappets are just marginally heavier than ordinary tappets and engage nearly no more space. Nevertheless, at the moment the Variocam Plus is just offered for the intake valves.

Advantage: VVT improves torque delivery at low / medium speed; Variable lift and duration lift high rev power.

Disadvantage: More complex and expensive

Who use it ? Porsche 911 Turbo, 911 Carrera 3.6

Example 3: Honda i-VTEC

If you know how VTEC and VVT-i works, you can easily imagine how to combine them into a more powerful VVT mechanism. Honda calls it i-VTEC. Like Toyota's VVTL-i, it provides:

- Continuous cam-phasing variable valve timing
- 2-stage variable valve lift plus valve-opening duration
- Can be applied to both intake and exhaust valves

Basically, the camshaft is purely VTEC - with different cam lobes for implementing 2-stage variable lift and timing. On the other hand, the camshaft can be phase-shifted by a hydraulic actuator at the end of the camshaft, so valve timing can be varied continuously according to need.

The i-VTEC was first introduced in Stream MPV, in which only the intake side applies i-VTEC. Theoretically, it can be applied to both intake and exhaust camshafts, but Honda seemed less generous than Toyota - even the Integra Type R uses only i-VTEC at intake side plus the regular VTEC at exhaust side.

Advantage: Continuous VVT improves torque delivery across the whole rev range; Variable lift and duration lift high rev power.

Disadvantage: More complex and expensive

Who use it ? 2.0 i-VTEC four for Stream, Civic, Integra and more to come.

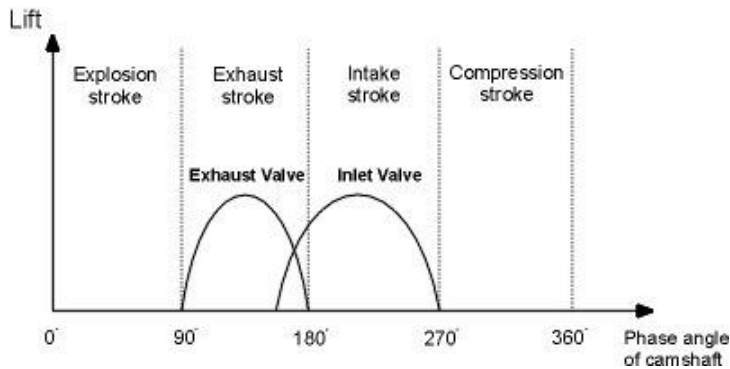
4) Rover's unique VVC system

Rover introduced its own system calls VVC (Variable Valve Control) in MGF in 1995. Many experts regard it as the best VVT considering its all-round ability - unlike cam-changing VVT, it provides continuously variable timing, thus improve low to medium rev torque delivery; and unlike cam-phasing VVT, it can lengthen the duration of valves opening (and continuously), thus boost power.

Basically, VVC employs an eccentric rotating disc to drive the inlet valves of every two cylinder. Since eccentric shape creates non-linear rotation, valves opening period can be varied. Still don't understand ? well, any clever mechanism must be difficult to understand. Otherwise, Rover won't be the only car maker using it.

VVC has one draw back: since every individual mechanism serves 2 adjacent cylinders, a V6 engine needs 4 such mechanisms, and that's not cheap. V8 also needs 4 such mechanism. V12 is impossible to be fitted, since there is insufficient space to fit the eccentric disc and drive gears between cylinders.

High Speed - Rover VVC



- | | |
|---------------|--|
| Advantage: | Continuously variable timing and duration of opening achieve both drivability and high speed power. |
| Disadvantage: | Not ultimately as powerful as cam-changing VVT, because of the lack of variable lift; Expensive for V6 and V8; impossible for V12. |
| Who use it ? | Rover 1.8 VVC engine serving MGF, Caterham and Lotus Elise 111S. |

VVT's benefit to fuel consumption and emission

EGR (Exhaust gas recirculation) is a commonly adopted technique to reduce emission and improve fuel efficiency. However, it is VVT that really exploit the full potential of EGR.

In theory, maximum overlap is needed between intake valves and exhaust valves' opening whenever the engine is running at high speed. However, when the car is running at medium speed in highway, in other words, the engine is running at light load, maximum overlapping may be useful as a mean to reduce fuel consumption and emission. Since the exhaust valves do not close until the intake valves have been open for a while, some of the exhaust gases are recirculated back into the cylinder at the same time as the new fuel / air mix is injected. As part of the fuel / air mix is replaced by exhaust gases, less fuel is needed. Because the exhaust gas comprise of mostly non-combustible gas, such as CO₂, the engine runs properly at the leaner fuel / air mixture without failing to combust.

Variable Intake Manifold

Variable intake manifold is increasingly more popular since the mid-90s. It is employed to boost low to medium speed torque without any drawback in fuel consumption or high speed power, thus improve flexibility of the engine. An ordinary fixed intake manifold has its geometry optimized for high speed power, or low speed torque, or a compromise between them. Variable intake manifolds introduce one or two more stages to deal with different engine speeds.

The result sounds like variable valve timing, but variable intake manifold benefits more low-speed torque than high-end power. Therefore it is very useful for sedans, which are heavier and heavier these days. For better drivability, there are also increasingly more sports cars feature variable intake manifold alongside VVT, these including Ferrari 360 M and 550M.

Compare with VVT, variable intake manifold is cheaper. What it needs are just some cast manifolds and a few electric-operated valves. In contrast, VVT need some elegant and precise hydraulic actuators, or even some special cam followers and camshafts.

There are two kinds of variable intake manifolds: variable length intake manifolds and resonance intake. Both of them make use of the geometry of intake manifolds to reach the same goal.

Variable length intake manifolds

Variable length intake manifolds is commonly used in sedans. Most designs employ 2 intake manifolds with different length to serve each cylinder. The longer one is for low-speed use. The shorter one is for high rev. It is easy to understand why high speed need a short manifold, because it enables freer and straightforward breathing. But why does it need longer pipe for low speed ? because longer pipe results in lower frequency of air mass reaching the cylinder, thus matches the lower rev of engine very much. This provide better cylinder filling, thus improves torque output. Besides, longer intake manifold leads to slower air flow, hence better mixing between air and fuel.



You can clearly see the manifolds of Ford's Duratec 2.5 litres V6 engine. Each cylinder has a long pipe and a short pipe.



Toyota's 2 litres Variable Intake engine also has a manifold longer than another

Some systems offer 3 stages of variable length, such as the one used by Audi's V8. How can Audi package all 3 manifolds for each cylinder, and a total of 24 manifolds in one engine? In fact, Audi doesn't use separate manifolds. Instead, it uses a rotary intake manifold with the inlet at the center of the rotor. The inlet rotate to different positions to form different length of manifold. The whole system recesses in the V-valley.

Resonance intake system

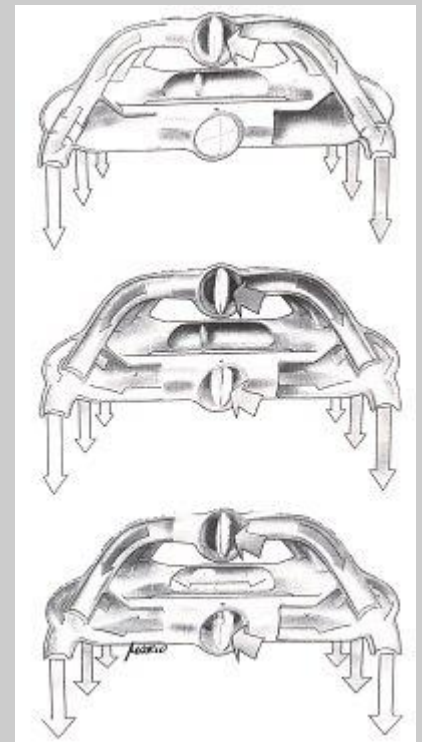
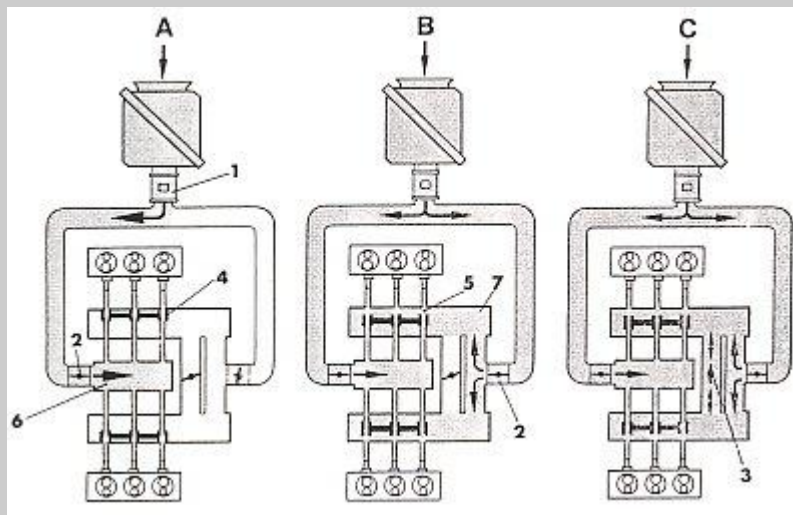
Boxer engines and V-type engines (but not inline engines) may employ resonance intake manifold to boost mid to high rev efficiency. Each bank of cylinders are fed by a common plenum chamber through separate pipes. The two plenum chambers are interconnected by two pipes of different diameters. One of the pipes can be closed by a valve controlled by engine management system. The firing order is arranged such that the cylinders breath alternately from each chamber, creating pressure wave between them. If the frequency of pressure wave matches the rev, it can help filling the cylinders, thus improved breathing efficiency. As the frequency depends on the cross-sectional area of the interconnecting pipes, by closing one of them at low rev, the area as well as frequency reduce, thus enhance mid-rev output. At high rpm, the valve is opened thus improves high-speed cylinder filling.



Porsche 996 GT3's resonance intake system. Note that 2 pipes connect between the 2 plenums.

Resonance intake system has been used in various Porsche starting from 964 Carrera. Since 993, Porsche combined it with an additional variable length manifold to form a 3-stage intake system names VarioRam. However, it is very space-engaging so that the 996 employs only the resonance intake system. Honda NSX is another rare applicant for resonance intake system.

Porsche's VarioRam



Below 5,000 rpm (left A and top right) : long pipes; resonance intake disabled.

5,000-5,800 rpm (left B and middle right) : long pipes plus short-pipe resonance intake, with one of the interconnected pipes of the resonance intake closed.

Above 5,800 rpm (left C and bottom right): long pipes plus short-pipe resonance intake, with both interconnected pipes of the resonance intake opened.

Summary of Variable Intake Manifolds

Advantage: Improves torque delivery at low speed without hurting high speed power; Cheaper than variable valve timing.

Disadvantage: A bit space engaging; no much benefit to high speed output.

Who use it ?

- Audi 2.0 four, V6 and S-models V8 - 2-stage variable length manifolds
- Audi A-models V8 - 3-stage variable length manifolds
- BMW new V8's DIVA - variable length manifolds, 2-stage ?
- Fiat / Alfa / Lancia Super Fire engines - 2-stage variable length manifolds
- Ferrari 360 Modena and 550 Maranello - 2-stage variable length manifolds
- Ford Duratec 2.5 and 3.0 V6 - 2-stage variable length manifolds
- Honda Integra Si 2.0, 3.2 V6 Type S - 2-stage variable length manifolds
- Honda Legend - 3-stage unknown system
- Honda NSX - 2-stage resonance intake
- Hyundai XG V6 - 2-stage variable length manifolds
- Jaguar 3.0 V6 - 3-stage variable length manifolds
- Mercedes V6 and V8 - variable length manifolds, probably 2-stage
- Nissan 3.0 V6 (Maxima), 2.5 inline-6 and V8 - 2-stage variable length manifolds
- Opel 3.2 V6 - 2-stage variable length manifolds
- Peugeot 2.2 four and 3.0 V6 - 2-stage variable length manifolds
- Porsche 996 Carrera / GT3 and all Boxsters - 2-stage resonance intake
- Renault Clio 2.0RS - 2-stage variable length manifolds
- Volkswagen group 1.6-litre four and VR6 - 2-stage variable length manifolds
- Volkswagen W8 - 2-stage resonance intake

Variable Back-Pressure Exhaust

More supercars now employ variable back-pressure exhaust. It is somewhat like the variable intake manifold, just locate at the exhaust. Normal exhaust pipes for sports cars collect exhaust pulse from individual cylinders and combine them to a larger pulse, with a corresponding lower pressure behind the pulse. This low pressure actually helps drawing more air / fuel mixture into the cylinder from intake manifolds. This is so-called "reverse supercharging".

The reverse supercharging work best at a certain engine rev which is determined by the length of the exhaust pipe. The shorter the pipe, the lower rpm the reverse supercharging works. Of course, for any fixed exhaust pipes, the choose of working rpm is always a compromise.

Variable back-pressure exhaust usually provides 2 different lengths of exhaust pipes. The switching between them is via opening and closing of valves. Therefore it satisfy both the requirements of high speed and low speed output. Moreover, it helps complying EU's noise regulations, which set upper limits according to speed.

Advantage: Optimize high and low speed output; reduce noise at low speed.

Disadvantage: Nil

Who use it ?

- Aston Martin Vanquish
- Ferrari 550 Maranello, 360 Modena
- Honda Integra Type R
- Lamborghini Diablo 6.0
- Mitsubishi Lancer Evo VII
- Nissan Sentra SE-R Spec V, Maxima, Cima (Infiniti Q45)

Multi-valve Engines

History

Multi-valve engines started life in 1912, adopted by a Peugeot GP racing car. It was briefly used by the pre-war Bentley and Bugatti. However, it was not applied to production cars until the 60s - Honda S600 was probably the earliest production road-going 4-valve car. In the 70s, there were several more 4-valve cars introduced, such as the Lotus Esprit (1976), Chevrolet Cosworth Vega (1975, engine made by Cosworth), BMW M1 (1979) and Triumph Donomite Sprint. The latter introduced the first single-cam 4-valve engine, using rocker arms to drive valves.



In the early 80s, when Ferrari had just adopted Quattrovalvole V8, Honda was introducing 3-valve engines to its mainstream bread-and-butter models. In the mid-80s, both Honda and Toyota made 4-valve engines standard in virtually all mainstream models. The Western car makers did that some 10 years later !

Theory

Improving breathing is one of the keys for power enhancement. Unquestionably, in the 2-valve era valves used to be the bottleneck, hence the need for more valves.

3-valve engines

The earliest mass production multi-valve engines were 3-valves because of its simple construction - it needs only a single camshaft to drive both intake valves and the exhaust valve of each cylinder. Today, there are still a few car cars using this cheap but inefficient design, such as Fiat Palio and all Mercedes V6 and V8 engines. Mercedes uses that because of emission rather than cost reason.

4-valve engines

A typical 2-valve engine has just 1/3 combustion chamber head area covered by the valves, but a 4-valve head increases that to more than 50%, hence smoother and quicker breathing. 4-valve design also benefits a clean and effective combustion, because the spark plug can be placed in the middle.

4 valves are better to be driven by twin-cam, one for intake valves and one for exhaust valves. Honda and Mitsubishi models prefer to use sohc, driving the valves via rocker arms like the aforementioned Triumph. This could be a bit cheaper, but introduce more friction and hurt high speed power. Therefore the sportiest Honda and Mitsubishi still use dohc.

5-valve engines

It is arguable that whether 5 valves per cylinder helps raising engine efficiency. Audi claimed it does, but fail to provide evidence to support. In fact, its 5V engines are no more powerful and torquey than its German rivals with 4 valves per cylinder.

Originally, 5-valve design doesn't guarantee covering more head area than 4-valver. Nevertheless, if the head of combustion chamber is in irregular shape like the picture shown, the valves may cover larger area. Ferrari F355 make use of this to enhance high-speed breathing. Is there any disadvantage? Yes, faster breathing also harm low-speed torque if no counter measure is taken. Therefore it is more suitable to sports cars.

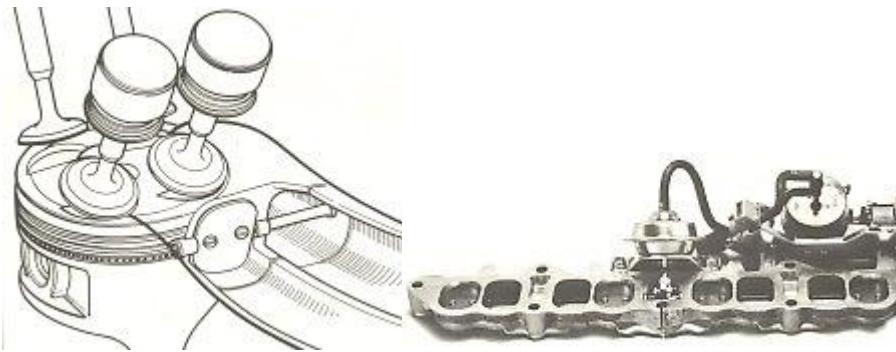
All existing 5-valve engines have 3 intake valves and 2 exhaust valves per cylinder, still arranged as cross-flow. The exhaust valves are larger, but in terms of total area intake valves are larger. In F355, by arranging the outer intake valves open 10° earlier than the center valve, it got the swirl needed for better air / fuel mixture, hence more efficient burning and cleaner emission.

The advantage of 5-valve engine is still under questioned. Not only few car makers used it (VW group, Ferrari and the bankrupted Bugatti), but Formula One cars also no longer favour it. Even the Ferrari F1 cars which was once famous for 5V engine has switched back to 4-valve design a few years ago.

Drawback and Solution - e.g. Toyota T-VIS

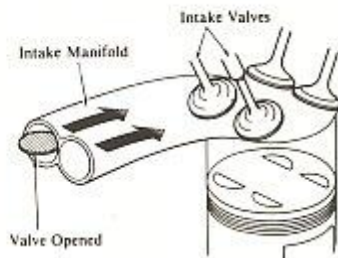
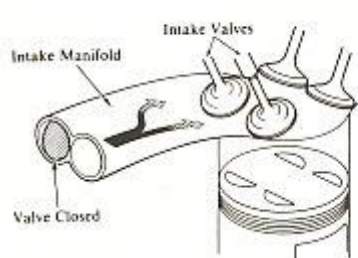
Most early 4-valve engines were not good at low-to-middle speed torque, simply because the larger intake area resulted in slower air flow. Especially at low speed, the slow air flow in the intake manifold led to imperfect mixing of fuel and air, hence knocking and reduced power and torque. Therefore 4-valve engines were regarded as strong at top end but weak at the bottom end, until the technology of variable intake manifold became popular recently. The aforementioned Chevrolet Cosworth Vega performed particularly weak at low speed.

In response to this, Toyota introduced T-VIS (Toyota Variable Intake System) in the mid-80s. T-VIS accelerated low speed air flow to the manifold. The theory was quite simple: the intake manifold for each cylinder was split into two separate sub-manifold which joint together near the intake valves. A butterfly valve was added at one of the sub-manifold. At below 4,650 rpm the butterfly valve would be closed so that raising the velocity of air in the manifold. As a result, better mixing could be obtained at the manifold (excluding direct-injection engines, fuel injection always takes place in the manifold).



Low to medium engine speed

High engine speed



However, for later mainstream sedan engines, Toyota dropped this idea and adopted a small-diameter intake manifold / port design. Many other car makers also went the same way, sacrificing a bit top end power to improve low speed flexibility. Today, the introduction of variable intake manifold can solve this problem.

Forced Induction

Turbocharging

Air intake system and Turbocharging

Most cars are **normally aspirated**, which means that air flows through an air filter and directly into the cylinders. High-performance engines are either **turbo charged** or **super charged**, which means that air coming into the engine is first pressurized (so that more air/fuel mixture can be squeezed into each cylinder) to increase performance. The amount of pressurization is called **boost**. A turbo charger uses a small turbine attached to the exhaust pipe to spin a compressing turbine in the incoming air stream. A super charger is attached directly to the engine to spin the compressor.

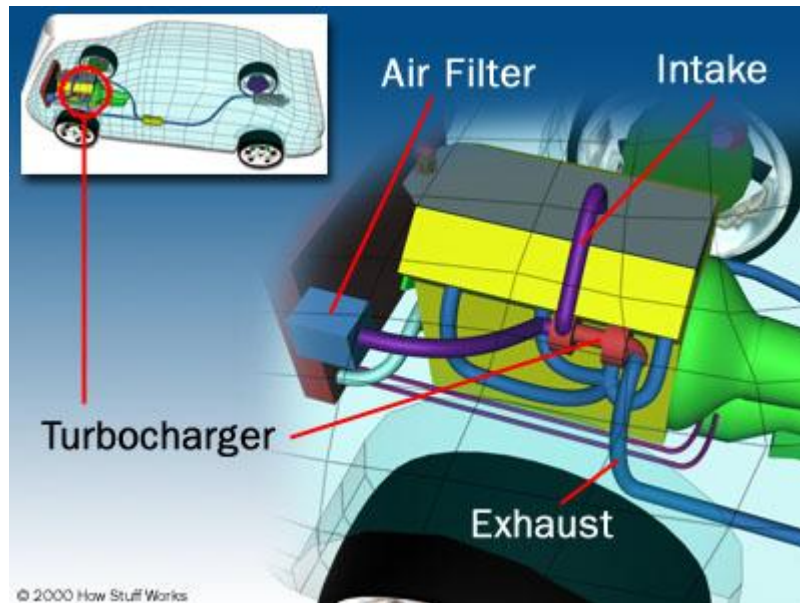


Photo courtesy [Garrett](#)

When people talk about [race cars](#) or high-performance sports cars, the topic of **turbochargers** usually comes up. Turbochargers also appear on [large diesel engines](#). A turbo can significantly boost an engine's horsepower without significantly increasing its weight, which is the huge benefit that makes turbos so popular!

Turbochargers are a type of **forced induction system**. They **compress** the air flowing into the engine. The advantage of compressing the air is that it lets the engine squeeze more air into a cylinder, and more air means that more fuel can be added. Therefore, you get more power from each explosion in each cylinder. A turbocharged engine produces more power overall than the same engine without the charging. This can significantly improve the power-to-weight ratio for the engine. In order to achieve this boost, the turbocharger uses the exhaust flow from the engine to spin a **turbine**, which in turn spins an **air pump**. The turbine in the turbocharger spins at speeds of up to 150,000 rotations per minute (rpm) -- that's about 30 times faster than most car engines can go. And since it is hooked up to the exhaust, the temperatures in the turbine are also very high.

One way to get more power out of an engine is to increase the amount of air and fuel that it can burn. One way to do this is to add cylinders or make the current cylinders bigger. Sometimes these changes may not be feasible -- a turbo can be a simpler, more compact way to add power, especially for an aftermarket accessory.



Where the turbocharger is located in the car

Turbochargers allow an engine to burn more fuel and air by packing more into the existing cylinders. The typical boost provided by a turbocharger is 6 to 8 pounds per square inch (psi). Since normal atmospheric pressure is 14.7 psi at sea level, you can see that you are getting about 50 percent more air into the engine. Therefore, you would expect to get 50 percent more power. It's not perfectly efficient, so you might get a **30- to 40-percent improvement** instead.

One cause of the **inefficiency** comes from the fact that the power to spin the turbine is not free. Having a turbine in the exhaust flow increases the restriction in the exhaust. This means that on the exhaust stroke, the engine has to push against a higher back-pressure. This subtracts a little bit of power from the cylinders that are firing at the same time.

The turbocharger also helps at **high altitudes**, where the air is less dense. Normal engines will experience reduced power at high altitudes because for each stroke of the piston, the engine will get a smaller mass of air. A turbocharged engine may also have reduced power, but the reduction will be less dramatic because the thinner air is easier for the turbocharger to pump.

Older cars with [carburetors](#) automatically increase the fuel rate to match the increased airflow going into the cylinders. Modern cars with [fuel injection](#) will also do this to a point. The fuel-injection system relies on oxygen sensors in the exhaust to determine if the air-to-fuel ratio is correct, so these systems will automatically increase the fuel flow if a turbo is added.

If a turbocharger with too much boost is added to a fuel-injected car, the system may not provide enough fuel -- either the software programmed into the controller will not allow it, or the pump and injectors are not capable of supplying it. In this case, other modifications will have to be made to get the maximum benefit from the turbocharger.

The turbocharger is bolted to the **exhaust manifold** of the engine. The exhaust from the cylinders spins the **turbine**, which works like a [gas turbine engine](#). The turbine is connected by a shaft to the **compressor**, which is located between the air filter and the intake manifold. The compressor pressurizes the air going into the pistons.

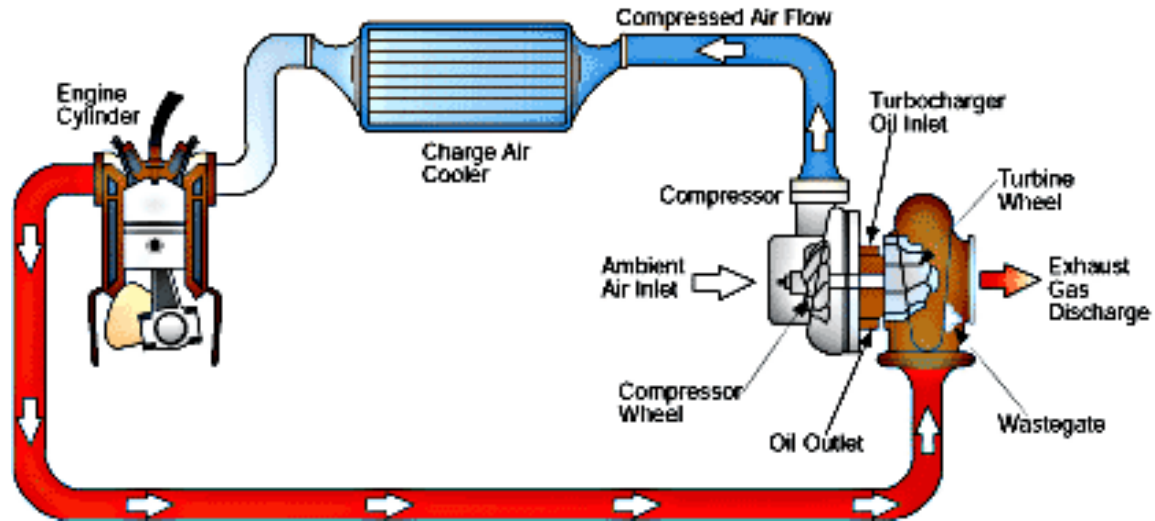


Image courtesy Garrett
How a turbocharger is plumbed in a car

The exhaust from the cylinders passes through the **turbine blades**, causing the turbine to spin. The more exhaust that goes through the blades, the faster they spin.

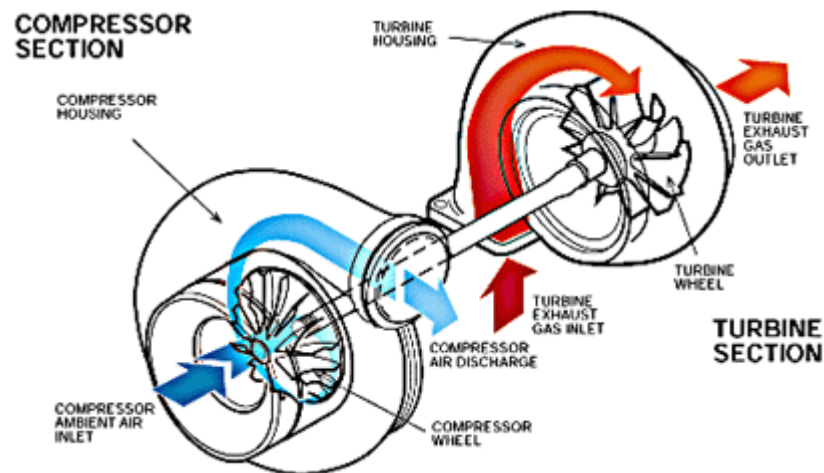


Image courtesy Garrett
Inside a turbocharger

On the other end of the shaft that the turbine is attached to, the **compressor** pumps air into the cylinders. The compressor is a type of centrifugal pump -- it draws air in at the center of its blades and flings it outward as it spins.



Photo

courtesy

[Garrett](#)

Turbo compressor blades

In order to handle speeds of up to 150,000 rpm, the turbine shaft has to be supported very carefully. Most bearings would explode at speeds like this, so most turbochargers use a **fluid bearing**. This type of bearing supports the shaft on a thin layer of oil that is constantly pumped around the shaft. This serves two purposes: It cools the shaft and some of the other turbocharger parts, and it allows the shaft to spin without much friction. There are many tradeoffs involved in designing a turbocharger for an engine. In the next section, we'll look at some of these compromises and see how they affect performance.

Design Considerations

Before we talk about the design tradeoffs, we need to talk about some of the possible problems with turbochargers that the designers must take into account.

Too Much Boost With air being pumped into the cylinders under pressure by the turbocharger, and then being further compressed by the piston, there is more danger of [knock](#). **Knocking** happens because as you compress air, the temperature of the air increases. The temperature may increase enough to ignite the fuel before the [spark plug](#) fires. Cars with turbochargers often need to run on higher [octane](#) fuel to avoid knock. If the boost pressure is really high, the compression ratio of the engine may have to be reduced to avoid knocking.

Turbo Lag

One of the main problems with turbochargers is that they do not provide an immediate power boost when you step on the gas. It takes a second for the turbine to get up to speed before boost is produced. This results in a feeling of lag when you step on the gas, and then the car lunges ahead when the turbo gets moving.

One way to decrease turbo lag is to reduce the **inertia** of the rotating parts, mainly by reducing their weight. This allows the turbine and compressor to accelerate quickly, and start providing boost earlier.

Small vs. Large Turbocharger

One sure way to reduce the inertia of the turbine and compressor is to make the turbocharger smaller. A small turbocharger will provide boost more quickly and at lower engine speeds, but may not be able to provide much boost at higher engine speeds when a really large volume of air is going into the engine. It is also in danger of spinning too quickly at higher engine speeds, when lots of exhaust is passing through the turbine.

A large turbocharger can provide lots of boost at high engine speeds, but may have bad turbo lag because of how long it takes to accelerate its heavier turbine and compressor.

Optional Turbo Features

The Wastegate

Most automotive turbochargers have a **wastegate**, which allows the use of a smaller turbocharger to reduce lag while preventing it from spinning too quickly at high engine speeds. The wastegate is a valve that allows the exhaust to bypass the turbine blades. The wastegate senses the boost pressure. If the pressure gets too high, it could be an indicator that the turbine is spinning too quickly, so the wastegate bypasses some of the exhaust around the turbine blades, allowing the blades to slow down.

Ball Bearings

Some turbochargers use **ball bearings** instead of fluid bearings to support the turbine shaft. But these are not your regular [ball bearings](#) -- they are super-precise bearings made of advanced materials to handle the speeds and temperatures of the turbocharger. They allow the turbine shaft to spin with less friction than the fluid bearings used in most turbochargers. They also allow a slightly smaller, lighter shaft to be used. This helps the turbocharger accelerate more quickly, further reducing turbo lag.

Ceramic Turbine Blades

Ceramic turbine blades are lighter than the steel blades used in most turbochargers. Again, this allows the turbine to spin up to speed faster, which reduces turbo lag.

Sequential Turbochargers

Some engines use **two turbochargers** of different sizes. The smaller one spins up to speed very quickly, reducing lag, while the bigger one takes over at higher engine speeds to provide more boost.

Intercoolers

When air is compressed, it heats up; and when air heats up, it expands. So some of the pressure increase from a turbocharger is the result of heating the air before it goes into the engine. In order to increase the power of the engine, the goal is to get more air molecules into the cylinder, not necessarily more air pressure.

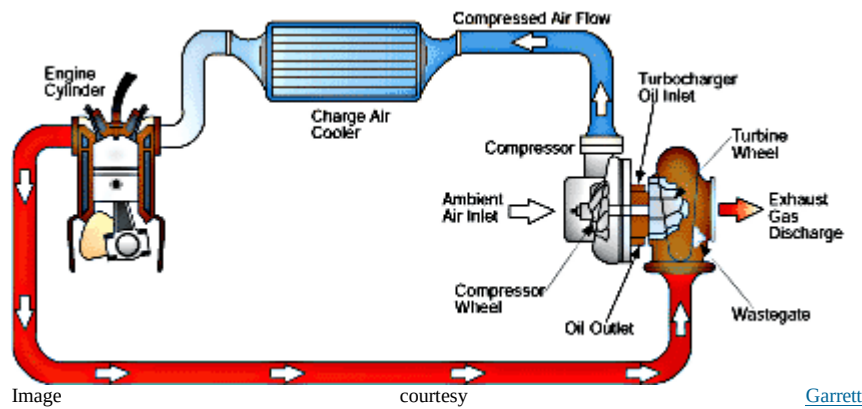


Image courtesy How a turbocharger is plumbed (including the charge air cooler)

An **intercooler** or **charge air cooler** is an additional component that looks something like a [radiator](#), except air passes through the inside as well as the outside of the intercooler. The intake air passes through sealed passageways inside the cooler, while cooler air from outside is blown across fins by the [engine cooling fan](#).

The intercooler further increases the power of the engine by cooling the pressurized air coming out of the compressor before it goes into the engine. This means that if the turbocharger is operating at a boost of 7 psi, the intercooled system will put in 7 psi of cooler air, which is denser and contains more air molecules than warmer air.

The advantage of turbocharging is obvious - instead of wasting thermal energy through exhaust, we can make use of such energy to increase engine power. By directing exhaust gas to rotate a turbine, which drives another turbine to pump fresh air into the combustion chambers at a pressure higher than normal atmosphere, a small capacity engine can deliver power comparable with much bigger opponents. For example, if a 2.0-litre turbocharged engine works at 1.5 bar boost pressure, it actually equals to a 3.0-litre naturally aspirated engine. As a result, engine size and weight can be much reduced, thus leads to better acceleration, handling and braking, though fuel consumption is not necessarily better.

Problems - Turbo Lag

Turbocharging was first introduced to production car by GM in the early 60s, using in Chevrolet Corvair. This car had very bad reputation about poor low-speed output and excessive turbo lag which made fluent driving impossible.

Turbo Lag was really the biggest problem preventing the early turbo cars from being accepted as practical. Although turbocharging had been extensively and successfully used in motor racing - started from BMW 2002 turbo and then spread to endurance racing and eventually Formula One - road cars always require a more user-friendly power delivery. Contemporary turbines were large and heavy, thus could not start spinning until about 3,500 rpm crank speed. As a result, low-speed output remained weak. Besides, since the contemporary turbocharging required compression ratio to be decreased to about 6.5:1 in order to avoid overheat to cylinder head, the pre-charged output was even weaker than a normally-aspirated engine of the same capacity !

Turbo lag can cause trouble in daily driving. Before the turbo intervenes, the car performs like an ordinary sedan. Open full throttle and raise the engine speed, counting from 1, 2, 3, 4 suddenly the power surge at 3,500 rpm and the car becomes a wild beast. On wet

surfaces or tight bends this might result in wheel spin or even lost of control. In the presence of turbo lag, it is very difficult to drive a car fluently.

Besides, turbo lag ruins the refinement of a car very much. Floor the throttle cannot result in instant power rise expected by the driver - all reactions appear several seconds later, no matter acceleration or releasing throttle. You can imagine how difficult to drive fast in city or twisted roads.

Porsche's solution to turbo lag



The first "practical" turbocharged road car eventually appeared in 1975, that's the Porsche 911 Turbo 3.0. To reduce turbo lag, Porsche engineers designed a mechanism allowing the turbine to "pre-spin" before boosting. The secret was a recirculating pipe and valve: before the exhaust gas attains enough pressure for driving the turbine, a recirculating path is established between the fresh-air-charging turbine's inlet and outlet, thus the turbine can spin freely without slow down by boost pressure. When the exhaust gas becomes sufficient to turbocharge, a valve will close the recirculating path, then the already-spinning turbine will be able to charge fresh air into the engine quickly. Therefore turbo lag is greatly reduced while power transition becomes smoother.

Intercooler

The 3.3-litre version 911 Turbo superseded the Turbo 3.0 in 1978. It introduced an intercooler at between the compressor and the engine. It reduced the air temperature for 50-60°C, thus not only improved the volumetric efficiency (in other words, the intake air became of higher density) but also allowed the compression ratio to be raised without worrying over heat to cylinder head. Of course, higher compression led to improved low-speed output.

Continuous development

During the 80s, turbocharging continued to evolve for better road manner. As the material and production technology improved, turbine's weight and inertia were greatly reduced, hence improved response and reduce turbo lag a lot. To handle the tremendous heat in exhaust flow, turbines are mostly made of stainless steel or ceramic (the latter is especially favoured by the Japanese IHI). Occasionally there are some cars employ titanium turbine, which is even lighter but very expensive.

A Titanium turbine from Mitsubishi Lancer GSR



Another area of improvement was boost control. The

early turbo engines employed mechanical wastegate to avoid over-pressurised the combustion chamber. Without wastegate, the boost pressure would have been proportional to the engine speed (because the speed of turbine depends on the amount of exhaust flow, hence the engine speed). At high rev, the pressure would have been too high, causing too much stressed and heat to the combustion chamber, thus may damage the engine. Wastegate is a valve added to the intake pipe. Whenever the pressure exceed a certain valve, wastegate opens and release the boost pressure.

The introduction of boost control in the late 80s took a great step forward from mechanical wastegate. While wastegate just set the upper limit of boost pressure, Electronic Boost Control governs the boost pressure throughout the whole rev range. For example, it may limit the boost to 1.4 bar for below 3,000 rpm, then 1.6 bar for 3,000 to 4,500 rpm and then 1.8 bar for over 4,500 rpm. This helps achieving a linear power delivery and contribute to refinement. Basically, Electronic Boost Control is just a wastegate activated by engine management system.

Twin-Turbo: Parallel or Sequential ?

The use of twin-turbocharger is a question of both efficiency and packaging. For larger engines, say, 2500 c.c. or above, it is better to use 2 smaller turbochargers instead of a big one, as small turbines reduce turbo lag. Today, performance cars no longer employ a large single turbo like the early 911 Turbo.



For V-shape and boxer engines, it is also recommended to use twin-turbo, because one turbo serves each bank shorten the turbo pipes and save a lot of space. Moreover, the shorter the pipes, the less turbo lag generates.

Some twin-turbo engines have the turbos arranged such that exhaust flow from one bank of cylinders drives a turbo which boost the intake of another bank. This is actually the concept of "feedback loop", which helps reaching power balance between two banks.

Most twin-turbo engines have the turbochargers arranged to operate independently, each serves one bank of cylinders. This is so-called "Parallel Twin-Turbo". An alternative arrangement, "Sequential Twin-Turbo", was designed to improve response and further reduce turbo lag. The turbos operate sequentially, that is, at low speed, all the limited amount of exhaust gas is directed to drive one of the small turbines, leaving another idle. Therefore the first turbine will accelerate quickly. When the exhaust flow reaches sufficient amount to drive both turbos, the second turbo intervenes and helps reaching the maximum boost pressure. Unfortunately, sequential twin-turbo requires very complicated connection of pipes (exhaust from both banks should reach both turbos; so do the intake pipes from both banks), thus is now losing interest from car makers. Porsche 959, Mazda 3rd generation RX7, Toyota Supra and Subaru Legacy are the only applicants as I know.

Light Pressure Turbo (LPT)

Light pressure turbocharging is one of the most popular power boosting technology in recent years. Saab, the pioneer of turbo in saloons, is the first car maker put it into mass production. In 1992, it surprised many by introducing the Saab 9000 2.3 turbo Ecopower. The engine had only 170 hp, that is, just 20 hp more than the normally aspirated version and 30 hp below the standard 2.3 turbo. Basically, it was just the standard engine with a smaller turbo and lighter boost pressure.

While other car makers were still pursuing "on paper" peak power, Saab's clever engineers realised that less equals to more. Despite of lower peak power, light turbo engine remains to be strong in torque, thus aids acceleration. Most important, it has very much better drivability due to the inexistence of turbo lag. Throttle response is nearly instant. Besides, Saab proved that the better torque curve enables taller gearing, thus actually delivering better fuel economy than a normally aspirated engine of the same size !

In the past, poor drivability and fuel consumption prevent turbocharging from adopting in main stream sedans. Now the trend is reversed - due to the increasing requirement of safety and comfort, modern cars are growing every year. Heavier weight asks for more power. For many four-cylinder sedans, they have 2 choices: either upgrade to six-cylinder or add a light pressure turbo. Of course the latter is more cost effective. It need no more space, adds little manufacturing cost, and burns less fuel than a 6-pot engine, therefore many other car makers also adopted it.

Advantage: Improve torque without adding much cost; furgical

Disadvantage: Nil

Who use it ?

- Volkswagen group 1.8T (150hp)
- PSA 2.0-litre turbo
- Saab 2.0, 2.3 and 3.0 Ecopower
- Volvo 1.9 and 2.4LPT.

Variable Turbine Geometry (VTG)

Variable Turbine Geometry technology is mostly used in turbo diesel engines, but there is no evidence that it could not benefit petrol engine. It is said that (don't ask me why): turbine makes best use of exhaust gas flow if the latter hit the blades at right angle under low speed, and at narrow angle under high speed. Variable Turbine Geometry mechanism therefore varies the direction of the exhaust nozzle according to speed, thus improve the acceleration of turbine.

Another Variable Turbine Geometry alters the cross-sectional area through which the exhaust gas flows, thus controls the amount of boost pressure. This is implemented by adjusting the position of guide vanes inside the turbocharger. At lower engine speeds, they restrict the flow and therefore increase boost pressure; at higher engine speeds they open wide and reduce the exhaust back-pressure.



Advantage: Improve turbine response without altering maximum boost pressure

Disadvantage: Nil

- Who use it ?
- Audi 1.9 TDi four, 2.5 TDi V6, 3.3 TDi V8 turbo diesel
 - BMW 2.0 four, 3.0 six and 4.0 V8 turbo diesel
 - Mercedes 2.2 CDI four, 2.7 CDI five and 3.2 CDI six turbo diesel

Supercharging



GM is one of the keen customers of supercharger. Most of its mid / full size sedans, such as the Pontiac Grand Prix GPX shown in here, have a 3.8 litres supercharged V6 to choose.

Before turbocharging arrived in the 60s, supercharging used to dominate the forced induction world. Supercharging, also called mechanical charging, appeared in around early 20s in Grand Prix racing cars in order to increase power. Since the compressor is driven directly by the engine crankshaft, it has the advantage of instant response (no lag). But the charger itself is rather heavy and energy inefficient, thus cannot produce as much power as turbocharger. Especially at high rev, it generates a lot of friction thus energy loss and prevent the engine from revving high.

A typical supercharger transforms the engine very much - very torquey at low and mid range rpm, but red line and peak power appear much earlier. That means the engine becomes lazy to rev (and to thrill you), but at any time you have a lot of torque to access, without needing to change gears frequently. For these reasons, supercharging is quite well suited to nowadays heavy sedans, especially those mated with automatic transmission. On the other hand, sports cars rarely use it.

The noise, friction and vibration generated by supercharger are the main reasons prevent it from using in highly refined luxurious cars. Although Mercedes-Benz has introduced a couple of supercharged four into the C-class, they are regarded as too unrefined compare with the V6 serving other versions.

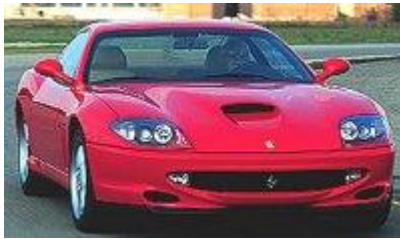
The introduction of light-pressure turbochargers also threaten the survival of supercharger. Volkswagen group, for example, dropped its long-standing G-supercharger and chose light-pressure turbo. Now supercharger is completely disappeared in budget cars, leaving just a few GT or sports sedans which pursue high torque without much additional to employ it. General Motors is perhaps the only real supporter to supercharger. It offers a 3.8-litre supercharged V6 for most of its budget mid to full-size sedans.

Advantage: Torquey and cheap

Disadvantage: Lack top end power, ruin revability, unrefined noise and vibration.

- Who use it ?
- Aston Martin DB7 3.2 six and Vantage 5.3 V8
 - GM 3.8-litre V6
 - Jaguar 4.0 V8 for XKR and XJR
 - Mercedes 2.0 and 2.3 four Kompressor
 - Mazda Miller Cycle V6
 - Subaru Pleo 0.66 four

Ram Air



You can clearly see ram air inlet in the bonnet of Ferrari 550 Maranello. Don't confuse it with inlet for intercooler, this car is not turbocharged !

Ram air device can also provide forced induction. When the car is travelling in speed, air will be forced into the engine manifold through the ram air inlet which usually locates on the top of bonnet. That create a slightly higher pressure than normal aspiration.

In fact, you can see ram air devices whenever you watch motor racing. The air box in every formula 1 race cars and the roof air inlet of GT race cars are all ram air devices. A Formula 1 engineer said a typical air box can gain 20 horse power when the car is running at 200 kph.

Advantage: Little additional cost

Disadvantage: Also little additional power, available in high speed only.

Who use it ?

- Ferrari 550 Maranello
- Lamborghini Diablo SV and GT
- McLaren F1
- GM Pontiac Firebird WS6 and Chevrolet Camaro SS

Twin Spark

Normal engines have one spark plug per cylinder. However, since decades ago, Alfa Romeo insisted to put 2 spark plugs in each cylinder. As ignition takes place in two locations rather than one, this enable more efficient combustion and cleaner emission. However, besides Alfa, in the past 15 years only Mercedes and Porsche have ever applied Twin Spark design to their engines. This is mainly because of the complexity of cylinder head - it would be too difficult to put 4 valves and 2 plugs into the small cylinder head area. (Mercedes' and Porsche's engines are 3 valves and 2 valves per cylinder respectively, so they have no such problem.) Only Alfa Romeo applied it to 4-valve engines.



Alfa's famous 2.0 TS engine

Advantage: Improves combustion efficiency, hence more power and cleaner emission.

Disadvantage: Benefits not convincing enough for most car makers

Who use it ? Alfa 1.6 to 2.0-litre engines, Mercedes V6 and V8

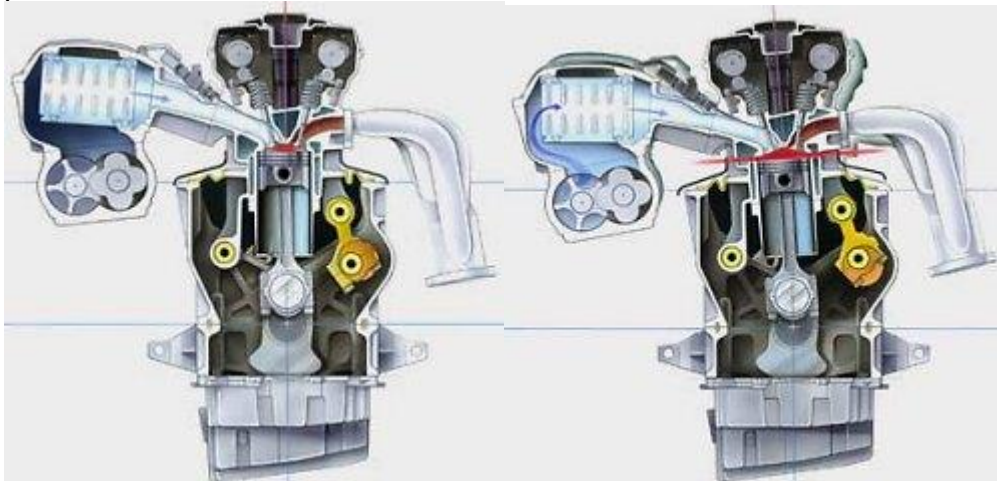
Variable Compression Ratio - Saab SVC

Saab has stunned the world by showing its variable compression ratio engine in the 2000 Geneva motor show. I've heard such engine for some 2 years, but this is the first time Saab disclose the details to the press. In my opinion, this is perhaps the largest single breakthrough in engine technology since turbocharging and electronic engine management.

Why is variable compression ratio so fascinating? As everybody knows, fixed compression ratio is always a constraint for supercharging or turbocharging engines. To prevent excessive pressure in combustion chamber, hence pre-ignite ("knocking") and overheat to cylinder head, turbo/supercharger engines always employ a much lower compression ratio than normally aspirated engines so that the total pressure won't exceed the limit when the boost pressure is added. The problem is, when the charger (especially is turbocharger) is not yet getting into full boost, that is, at low and mid rev, the combustion runs at lower compression ratio than normally aspirated engines. Therefore power efficiency at low speed is even lower than normally aspirated engines.

I remember when I was still 13 or 14 years old, I realized that problem and "designed" a variable compression ratio engine on paper. It involved variable length connecting rods to vary the position of piston's top dead center, hence compression ratio. When the turbo is not in full boost, compression ratio is as high as normally aspirated engine (10:1 by then). This lower to 7:1 for full boost. Of course, that concept is completely out of imagination and is no way to be feasible. Today - a dozen years later - Saab finally realized the variable compression ratio engine.

Named SVC (Saab Variable Compression), the engine implement VC by an innovative and interesting method - slidable cylinder head and cylinder. Let's look at the following pictures for illustration.



Left: high compression ratio; Right: low compression ratio

As seen, the SVC engine have a cylinder head with integrated cylinders - which is known as monohead. The monohead is pivoted at the crankcase and its slope can be adjusted

slightly (up to 4 degrees) in relation to the engine block, pistons, crankcase etc. by means of a hydraulic actuator, therefore the volume of the combustion chamber (when piston is in compressed position) can be varied. In other words, compression ratio is also variable.

SVC is cleverer than any previous patents for variable compression ratio engines is that it involves no additional moving parts at the critical combustion chamber or any reciprocating components, so it is simple, durable and free of leakage.

The monohead is self-contained, that means it has its own cooling system. Cooling passages across the head and the cylinder wall. There is a rubber sealing between the monohead and engine block.

The VC allows the Saab engine to run on very high supercharging pressure - 2.8 bar, compare with the latest 911 turbo's 1.94 bar, or about twice the boost pressure using by 9-3 Vigen. So high that today's turbochargers cannot provide. Therefore it employs supercharger instead. At other speed, the VC is adjustable continuously according to needs - depends on rev, load, temperature, fuel used etc., all decided by engine management system. Therefore power and fuel consumption (hence emission) can be optimized at any conditions.

The SVC engine shown in Geneva is the third generation prototype, although production is still far away. It is an inline 5-cylinder with 4-valve head. The displacement is just 1598 c.c. to take advantage of the outstanding efficiency. Compression ratio can be varied between 8:1 and 14:1. With the supercharger, it output a maximum 225 hp and 224 lbft, something similar to a Honda 3.2-litre V6. However, its fuel consumption is very low. Saab claims it saves 30% compare with equally powerful conventional engines.

In terms of specific output, it achieve 150 hp per litre, which must be a world record for production car. At the same time, it is expected to fulfill all foreseeable emission regulations, including the tightest EU4. Another advantage is the suitability to different grade of fuel, especially in America where lower Octane gas is common. The engine management system detect the fuel grade and decide the most appropriate compression ratio to be used.

Saab started developing SVC in the late 80s and acquired the first patent in 1990. The first prototype was a 2-litre unit but was considered as more powerful than needed. The second prototype was a 1.4-litre inline-6 but it had problems about packaging, so the inline-5 configuration was eventually chosen.

More work has to be done to make a SVC into production. The production unit might not be the same as this one, but it is believed that General Motors has green lighted the full development, which requires big investment from parent company.

Advantage: Enhance efficiency a lot for turbo/supercharged engines across the whole rev range, thus enable the engine to be smaller and lighter; highly adaptable to different grade of fuel; cleaner emission possible.

Disadvantage: Engine head and block more complicated

Who use it ? Only Saab is developing.

Engine Smoothness

A refined engine should be smooth, free of vibration and quiet. These qualities also help the engine to spin freer at high rpm, raising red line, hence power.

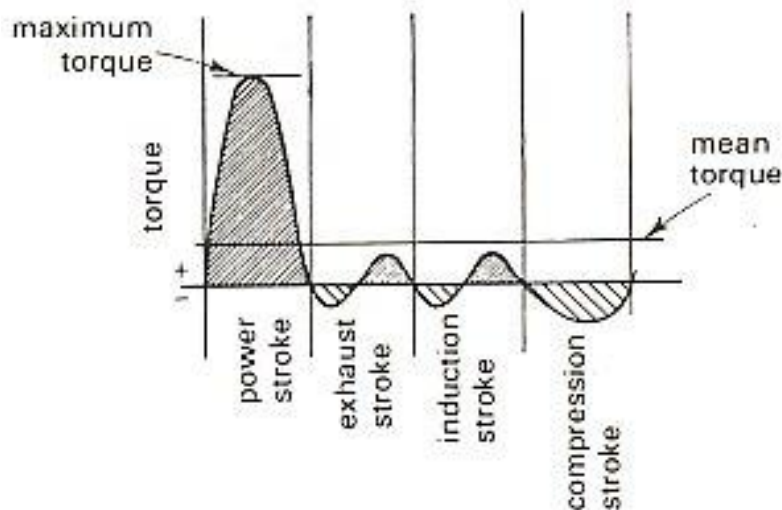
Engine smoothness depends very much on the basic configuration of the engine design - no. of cylinders, how the cylinders are arranged (in-line, V-shape or horizontally opposed) and the V-angle for V-shape engines. In case a less favourable configuration is chosen, probably due to packaging or cost reasons, counter weights or balancer shafts may be used to counter the vibration generated in the price of a little bit energy loss.

Strengthening of the engine block, crankshaft etc. can absorb certain level of vibration and noise. Lastly, the use of lower friction parts can further enhance smoothness and quietness.

A cylinder takes 720° crankshaft angle (i.e., 2 revolutions) to complete 1 cycle of 4-stroke operation. In other words, it fires once every 2 crankshaft revolutions. Only the power stroke (expansion stroke) generates positive power, while intake stroke, exhaust stroke and compression stroke consume power, especially the latter. Therefore a single-cylinder engine generates power in the form of periodic pulse. The picture below shows how the power be delivered. To smooth the power delivery, all engines must employ a heavy flywheel, using its inertia to keep the engine running roughly at constant speed. Of course, the heavier the flywheel, the smoother the power delivery becomes, but it also makes the engine less responsive. Therefore the pulsation manner of the engine cannot be completely eliminated by a reasonably large flywheel.

Therefore we need multi-cylinder engines. While single-cylinder engine fires once every 2 revolutions, twin-cylinder engine fires once every revolution, 3-cylinder fires once every $720 / 3 = 270^\circ$ crank angle, 4-cylinder fires once every 180° (half a revolution) 12-cylinder engine fires once every just 60° crank angle. Obviously, the more cylinders the engine has, the smoother the power delivery becomes.

This explains why we prefer V12 engines than in-line 6, although both of them achieve near perfect internal balance.



Cause of vibration

Vibration is caused by the movement of the internal parts, especially are pistons and connecting rods. The piston and con-rod move up and down periodically without counter balanced by other means. If the engine is a single-cylinder engine, it will jump up and down periodically as well.

In reality, the direction of vibration is not just vertical. Because the connecting rod is not just travelling upward and downward, but also left and right, there is also some vibration in transverse direction; However, compare with piston, connecting rod is much lighter, thus the vibration generated by the left / right movement of con-rod is also much smaller than the up / down vibration by the piston.

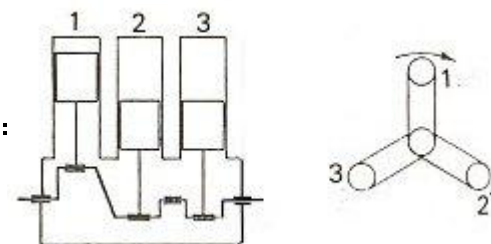
Inline 2-cylinder engines

As the engine fires once every revolution (or $720^\circ / 2 = 360^\circ$ crankshaft angle), the two pistons run exactly in the same direction as well as position. That means the total vibration will be twice the magnitude of that generated by one cylinder. The direction of vibration is mostly upward / downward.

This is the worse engine configuration for refinement, therefore only the cheapest mini cars in the past employed it, such as Fiat 128, entry-level Fiat Cinquecento and Honda Today etc. Today, I'm afraid there is probably no mass production car still use twin-cylinder engines, not even the smallest Japanese K-cars. Although the displacement of K-cars is 660 c.c. and is theoretically more suitable to twin-cylinder, they employs 3-cylinder or even four-pot to avoid the severe vibration problem of twin-cylinder.

Inline 3-cylinder engines

As the engine fires once every 240° crankshaft angle ($720^\circ / 3 = 240^\circ$), the crankshaft design is as shown in the below picture. (Firing order is: 1-3-2)

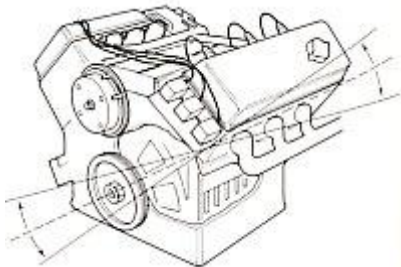


It seems that no matter how the crankshaft rotate, the combined center of gravity of all 3 pistons and con-

rods will remain at the same location, hence no vibration generated. By mathematical analysis, you can also find there is no forces generated in vertical direction as well as transverse direction. (actually, I really performed such calculations) So why did we hear that 3-cylinder engine need balancer shaft ?

In fact, the calculation is wrong because it assumes the engine is one point, thus the forces of all 3 cylinders act on this single point and result in complete cancellation. In reality, the forces act on 3 different locations on the crankshaft, thus instead of canceling one another, they make the crankshaft vibrating end to end.

Don't understand ? look at the above picture, the side view of the engine. Piston 1 is at the top now and is going downward, thus generates an upward force to the left end of the crankshaft. Piston 2 is also going downward, thus generates an upward force to the middle of the crankshaft. Piston 3 is going upward, thus generate a downward force to the right end of crankshaft. As the engine's center of gravity locates in cylinder 2, you can see forces from piston 1 push the left end of the engine upward while forces from piston 3 push the right end of the engine downward; After 180° rotation, the situation will be completely reversed - downward force at left and upward force at the right. In other words, this is an end-to-end vibration with respect to the center in cylinder 2.



End-to-end vibration (shown here is a V6)

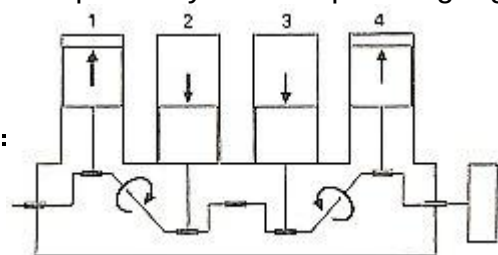
Solution - single balancer shaft

Therefore inline-3 engine is better to be equipped with a balancer shaft, driven by crankshaft. There is a weight at each end of the balancer shaft. The weights move in direction opposite to the direction of the end pistons. When the piston goes up, the weight goes down. When the piston goes down, the weight goes up. Therefore the end-to-end vibration can be counter balanced by the balancer shaft which is driven at the same speed as the crankshaft.

Inline 4-cylinder engines (versus boxer 4-cylinder)

As commonly known, big straight-four engine requires twin-balancer shafts rotating at twice the frequency as the crankshaft to reduce vibration. This is very different to 3-cylinder engines, which need a single balancer shaft running at the same frequency as crankshaft. Obviously, the vibration generated by straight-four engines is not the same as 3-cylinder engines.

I did some research into this topic by mathematical analysis, also wrote a program to simulate the vibration. The result is exactly the same as found in any textbooks. However, to explain to you in simpler language, let us see in this way ...

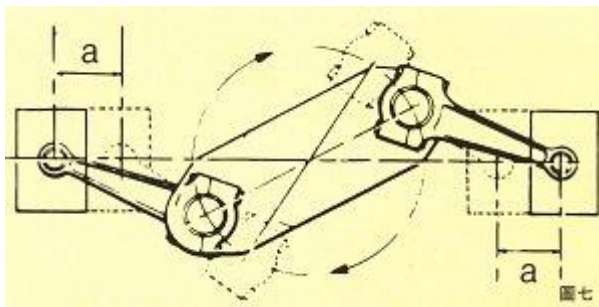


The left pictures shows an inline-4 engine. It fires once every $720^\circ / 4 = 180^\circ$ crank angle, hence 2 of the pistons are in exactly the same position and move

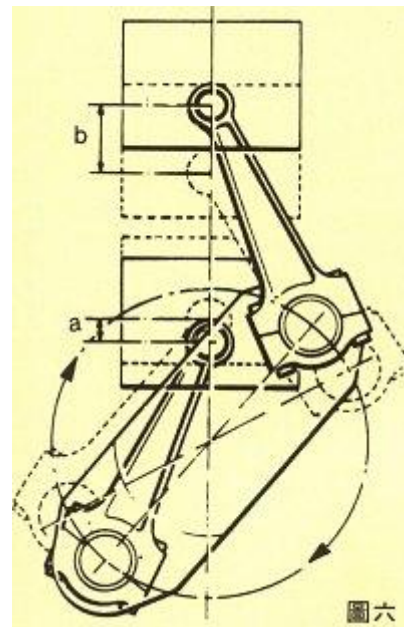
in the same direction, while the remaining 2 pistons are also a pair. To avoid the end-to-end vibration as experienced in 3-cylinder engines, car makers always arrange the pistons as shown in the picture, that is, symmetrical. In other words, piston 1 and 4 are a pair, while piston 2 and 3 form another pair. Therefore movement of piston 1 will be balanced by the symmetric piston 4. The same goes for piston 2 and 3.

That's just the end-to-end vibration with respect to the engine center. What about the resultant upward / downward vibration ? It seems that the movement of piston 1 is counter balanced by piston 2, while piston 3 counters piston 4. However, this is just skin-deep. More professional speaking, that just proves the balance of 1st order force. The second order force (which can be derived from equation) is normally much smaller than the 1st order force and it is rotating at twice the frequency of the 1st order force. Nevertheless, the configuration of inline-4 actually multiplies the magnitude of 2nd order force thus making it hard to be ignored, especially is for larger engines.

A simpler explanation is given in the below pictures, which compare a perfectly balanced boxer-4 engine with an inline-4 engine.



Boxer (horizontally-opposed) engine



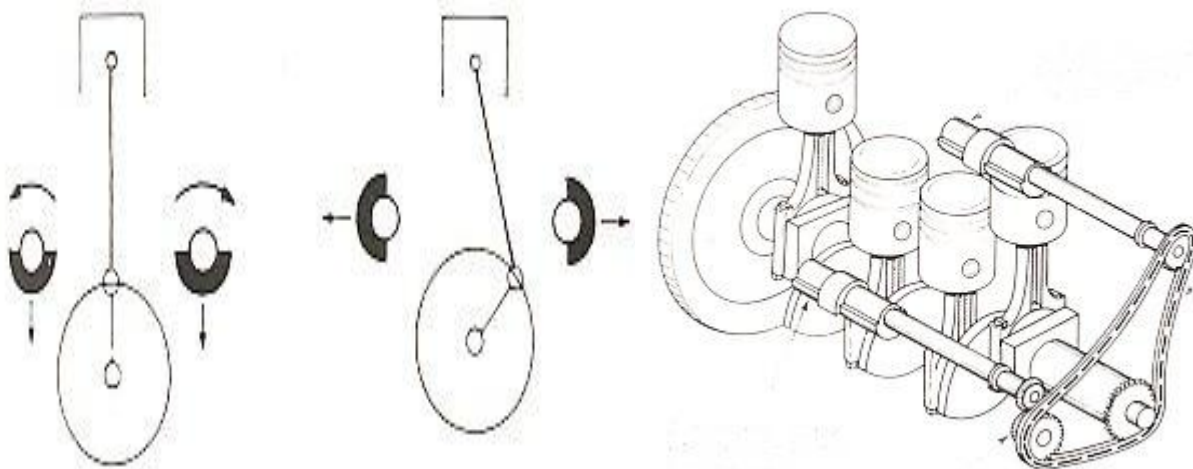
Inline engine

As seen, no matter where the crankshaft rotates to, the boxer engine has the pair of pistons always in opposite positions, directions and speeds, thus all the forces can be balanced. (if not for packaging and cost reason, boxer engines would have been the best choice) In contrast, in a straight-four engine, rotate the crankshaft a certain angle, the piston near the top end has a displacement (b), larger than that of another piston near the bottom (a). As vertical force is the product of displacement and mass of piston and divided by the time taken for such displacement, you can see the different displacements must lead to different forces, therefore complete cancellation is impossible. The resultant force is the aforementioned second order force, which rotates at twice the speed of the crankshaft.

Solution - Twin-balancer shafts

The longer the stroke, the heavier the pistons and con-rods, the more second order vibration generates. Unfortunately, car makers favour straight-four engine for its advantages of low cost and compact dimensions. Since the 80s, car engineers regard 4-pot engines larger than 2 litres in capacity had better to be equipped with twin-balancer shafts to dampen the vibration. Although the strengthening of engine block, the use of hydraulic engine mount and lightweight pistons helped breaking such rule, the trend of pursuing refinement once again led to many engines larger than 2 litres to use balancer shafts.

Balancer shaft was invented by British automotive engineering master Dr. Frederick Lanchester in the early 20th century. Mitsubishi obtained the patent and put it into mass production in the 1976 Colt Celeste 2000, then Fiat group used it in its Lamda engine series, including the 1.6-litre Delta HF turbo and Fiat Croma / Lancia Thema's 2-litre turbo. Meanwhile, Saab 9000 and Porsche 944 also introduced it into their powerful inline fours. All these car makers obtained license from Mitsubishi.



To deal with second order vibration, a pair of balancer shafts is needed, driven by the engine and rotate in opposite directions to each other, at twice the speed of the crankshaft. They locate in either sides of the engine. One of them is positioned just above the crank shaft level, the other is far above. Counter weights on the balancer shafts will completely cancel the second order force, thus result in a silky-smooth rotation.

The use of 2 balancer shafts instead of a large single one is because the vibration generated by the engine is mostly in vertical direction. 2 shafts rotating in opposite direction can cancel each other's transverse force and result in a net vertical force which is used to balance the vibration.

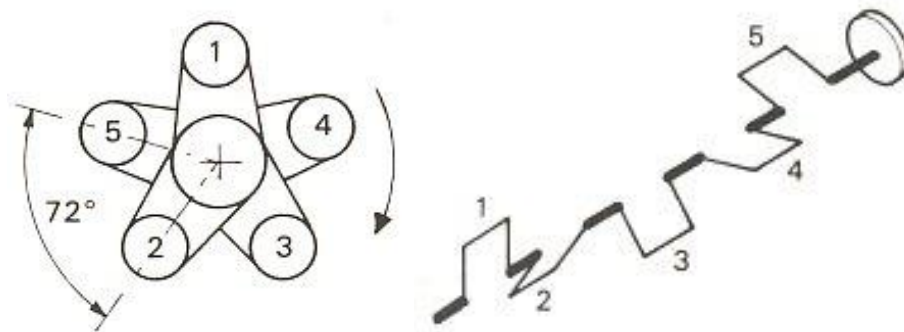
Without twin-balancer shaft, Porsche would have been impossible to make the 3-litre inline-four which powered the 944 S2 and 968. That's the biggest four-cylinder engine in modern cars.

Inline 5-cylinder engines

Straight-five engine is not very common in motor industry. In the past 20 years, only Audi (2.2 and 2.3-litre), Honda (Acura TL), Volvo (2.0-litre, 2.3 turbo and 2.4-litre), Fiat group (2.0 and 2.4-litre Super Fire series) and Mercedes diesel adopted such design. However,

straight-five engine has its own advantages. Firstly, it bridges the gap between 4 and 6-cylinder engines, thus may offer the best cylinder capacity for optimized efficiency; Secondly, compare with 4-cylinder engines, it saves one balancer shaft; Thirdly, compare with 6-cylinder engines, it is short enough to be fitted transversely into the engine compartment of front-wheel-drive cars, driving directly the inline gearbox. Lastly, it can be derived from a modular design consisting of 4 and 6-cylinder inline engines, not only saving development cost but also eliminating the investment of a new production line. Fiat, Mercedes and Volvo's 5-pots, for example, are made as modular engines.

The inline-5 engine fires once every $720^\circ / 5 = 144^\circ$ crank angle. As a result, the crankshaft design is as shown in below. Firing order is 1-3-5-4-2.



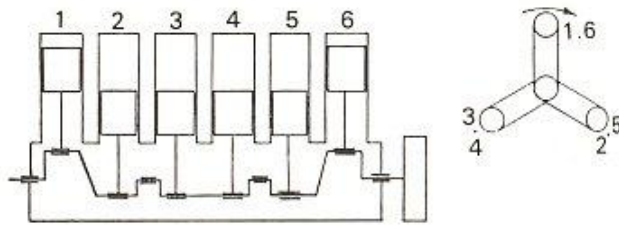
The mathematical analysis proves that both its resultant first order force and second order force are balanced. Therefore it doesn't need the twin-balancer shafts as a big 4-cylinder engine. However, it generates end-to-end vibration like 3-cylinder engines, because piston 1 is not in the same position as piston 5, and piston 2 is not in the same position as piston 4. Therefore both ends of the engine will vibrate up and down with respect to the engine center.

Solution - single balancer shaft

Obviously, the solution is the same as 3-pot engines, that is, employ a balancer shaft on which there are counter weights moving in the opposite direction to the pistons. The balancer shaft is driven by the engine at the same speed as the crankshaft.

Is that enough to make 5-cylinder engine as smooth as 6-cylinder? no. For packaging reasons, the balancer shaft cannot be placed in the most optimized position, that is, right above or below the crankshaft. Therefore it has to be offset to either side of the engine, resulting in incomplete cancellation of vibration.

Inline 6-cylinder engines



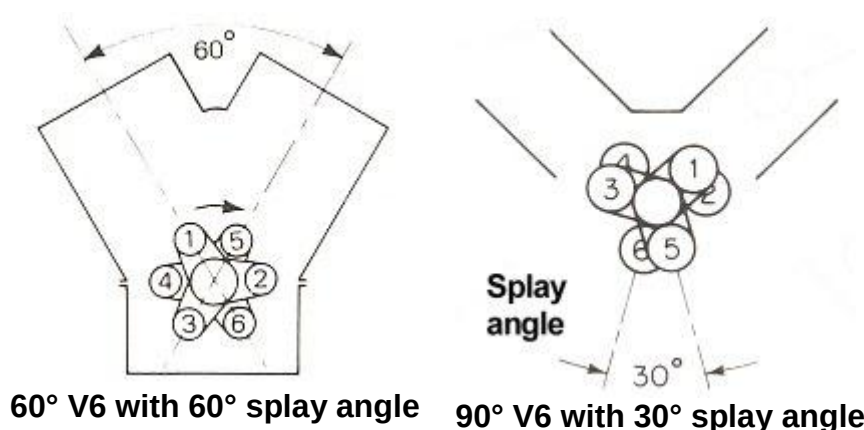
As shown in the picture, straight-6 engine is simply two 3-cylinder engines mated symmetrically together, thus piston 1 is always in the same position as piston 6, piston 2 the same as piston 5 in other words, the engine is balanced end-to-end and requires no balancer shaft, unlike 3-cylinder engines.

What about vertical / transverse forces? like 3-cylinder engines, the vertical and transverse forces generated by individual cylinders, no matter first order or second order, are completely balanced by one another. The resultant vibration is nearly zero, thus inline-6 is virtually a perfect configuration.

Inline-6 is not the only configuration can deliver near perfect refinement, but it is the most compact one among them. All boxer engines are perfectly balanced, but they are too wide and require duplicate of blocks, heads and valve gears. V12 engines also achieve perfect balance, but obviously out of the reach of most mass production cars. Automotive engineers knew that long ago, that's why you can see most of the best classic engines were inline-6, such as Rolls-Royce Silver Ghost, Bentley Speed Six, Mercedes SSK, many Bugattis, Jaguar XK-series and BMW's various models.

V6 engines

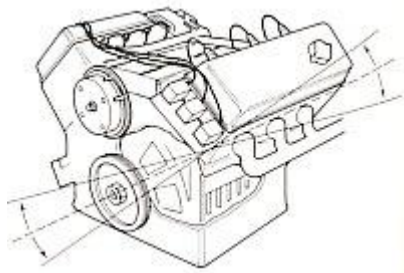
V6 engines, excluding Volkswagen's 15° VR6 (to be discussed later), are not just made from splitting inline-6 into two banks arranged in V-shape. A V6 has a very different crankshaft - only 4 main bearings instead of 7. In other words, between two adjacent bearings there are crank throws for 2 cylinders, one from bank A and another from bank B. While V8 engines have those 2 cylinders shared the same crank pin, V6 engine has to split the crank pin into two pieces, with a splay angle between those pins (30° splay angle for 90° V6; 60° splay angle for 60° V6). These are shown in below.



Split crank pins with a 30° splay angle

For better balance, most V6s are arranged such that the banks are placed at either 60° or 90° to each other. In this way, the movement of cylinders in bank A matches those in bank B, thus there is no vibration generated between banks. Besides, like 3-cylinder engines, there is no vertical and transverse vibration.

However, both 60° or 90° V6s have somewhat end-to-end vibration like 3-cylinder engines, especially is for 90° V6. (sorry, I don't have the theory) It needs a counter-rotating single balancer shaft, at crank speed, to suppress the vibration. The balancer shaft is located inside the V-valley, so it is not space engaging. On the other hand, 90° V6 has a decisive advantage in production point of view - it can be machined in V8's production line because both of them are 90°. (unlike V6, V8 can only be optimised at 90°) This save a lot of production cost. An example is Mercedes' supersmooth 2.4 to 3.2-litre V6s, which share the same architecture with V8s but added with a balancer shaft.



End-to-end vibration



Single balancer shaft inside the V-valley

60° V6 is smoother to the extent that, with adequate design engine mount, most of them could be made nearly as smooth as inline-6 engines without the need of balancer shaft. It is also narrower, so easier to be packaged into a FWD cars, mounted transversely.

60° V6 versus Inline-6

As space efficiency becomes more and more important, most car makers favour V6. The most influential V6 was perhaps Alfa Romeo's 2.5-litre 60° V6 used in the GTV6. It established a reputation for V6 that it can be compact, powerful and smooth. An equivalent inline-6 would have never fit the small and sloping engine compartment of that car. Compare the shape of BMW with the Alfa and you'll know the packaging advantage of V6s.

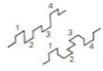
Straight-six engines are nearly impossible to be used in front-wheel drive cars as well. Even a car as wide as Volvo S80 has to introduce the world's shortest gearbox in order to make space for the 2.9-litre straight-six mounted transversely in the engine compartment. Longitudinal mounted inline-6 doesn't have such problems, but it engages too much space in north-south direction, thus engage some space which would have contributed to cockpit room.

However, BMW is still loyal to inline-6 engines. Ultimately, inline-6 engine is more efficient yet smoother. V6 has more energy loss because it duplicates valve gears and camshafts (which increase frictional loss), while the use of 2 cylinder banks leads to more heat loss. In terms of production cost, although V6 has 3 fewer main bearings, it has more valve gears - which is getting more and more costly these days, with the introduction of twin-cam, hydraulic tappets / finger follower and variable valve timing. Inline-6 is going to be cheaper than equivalent V6.

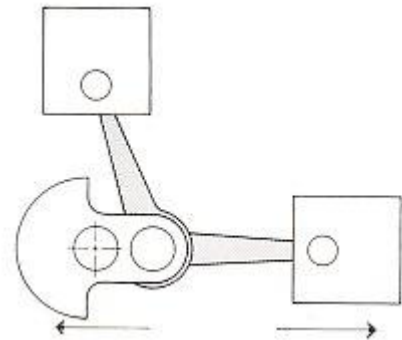
V8 engines

90° is the only configuration achieving good balance for V8. However, there are two types of crankshaft arrangements, which delivers very different characters. They are cross-plane

crankshaft and flat-plane crankshaft. Most of the world's V8s are cross-plane V8, including all American V8s and all sedans' V8s. However, the most exotic European sports cars, including Ferrari, Lotus and TVRs, employ flat-plane V8s.



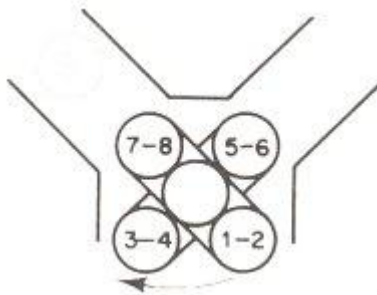
Flat-plane V8 (left) and Cross-plane V8 (right)



Share the same crank pin

No matter which kind of V8s, they have 5 main bearings. A cylinder in bank A shares the same crank pin with the corresponding cylinder in bank B, therefore the crankshaft of V8 is actually simpler than V6. Both V8s generate no vibration in vertical, transverse directions or between bank and bank.

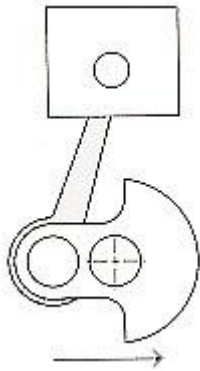
Cross-plane V8



vibration.

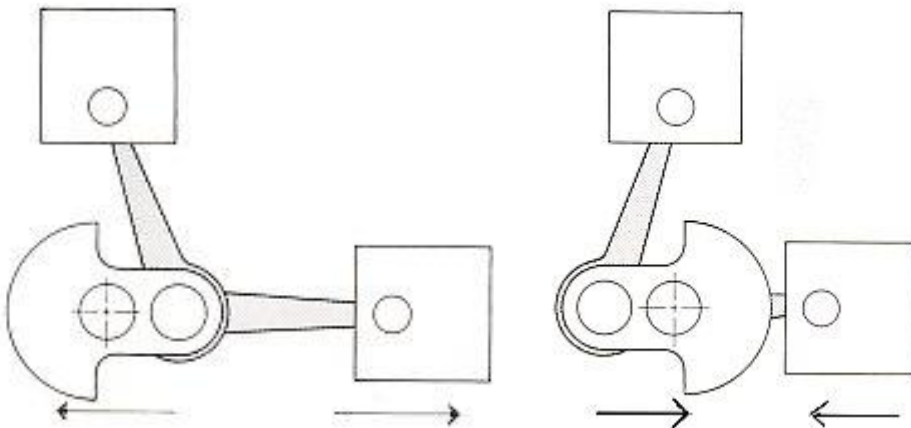
However, for cross-plane V8s, there is vibration from end to end of the engine, this is because the first piston of bank A is not in the same position as the last piston of bank A (the same goes for bank B), unlike an inline-4 engine. No problem, the 90° V8 solves this problem by introducing an extra-heavy counter weight to every cylinder. The counter weight is heavy enough to balance the weight of crank throw, con-rod and piston of that cylinder, thus resulting in lack of

Now you must be wondering why such counter weight is not used in other kinds of engines. It is because this counter weight must be used in 90° V-type engines which have shared crank pins. In our previous study, you'll find only V8 fulfills all these requirements. Why are there such requirements? good question. As you know, all engines have counter weights just enough to balance the weight of crank throws and part of the connecting rods, leaving the remaining weight of connecting rods and the whole, all-important pistons unbalanced. This is because the rotating counter weight can only balance rotating mass. Unluckily, the whole piston moves vertically rather than rotates about the crankshaft, while the CG of con-rod is somewhat rotating but also somewhat going up and down. If we insist to use heavy counter weight, it will cause side shake.



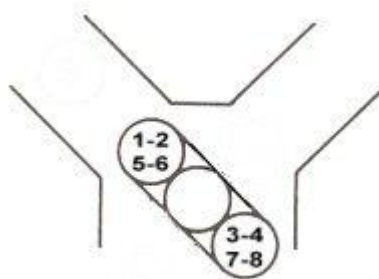
Considering the illustration. Assume the counter weight in vertical position is heavy enough to balance the crank throw, con-rod and pistons. When the crankshaft rotate 90° , the counter weight is repositioned to the right, but the piston doesn't go to the left, and the con-rod just partially moves to the left. Only the crank pin moves completely to the left. Now you can see the system is not balanced. The counter weight will generate a net force towards the right.

However, for 90° V8, when such a heavy counter weight moves to the right, the piston from another bank will cancel it completely, because their movement are exactly opposed at this moment. (see illustrations below) The same result can be found for the counter weight moving to the left. Therefore 90° cross-plane V8 employs full-weight counter weights can achieve near perfect smoothness.



Flat-plane V8 for high performance cars

However, the disadvantage of cross-plane V8s is also about the counter weights - not only increase the weight of engine, they also contribute to rotational inertia, thus making the engine less responsive and less revvy, dropping upper rev limit and top-end power. Moreover, the larger counter weights usually requires a larger crankcase to house them, thus raising the height (and more important, center of gravity) of the engine. Therefore Ferrari all V8 models, TVR Cerbera AJP V8 and Lotus Esprit V8 employ flat-plane V8s instead.



Flat-plane V8 is named according to the shape of the crankshaft, which is in a flat plane. It is very much like two inline-4 engines mated together. In particular, it achieves end-to-end balance because the first piston and last piston of a bank is exactly in the same position, so are the center two pistons. This is just the same as straight-four engines, therefore the sound of flat-plane V8 is usually somewhat like a pair of four-pot engines screaming simultaneously, unlike the

rumble-bumble of cross-plane V8s.

As both banks run like an inline-4 engine, there is second-order vibration. For a 90° flat-plane V8, the sum of second-order force generated in the 2 banks is - by simple vector analysis - 1.41 times (root-2) of the force generated by each of the inline-4 it consists of. And the direction of vibration is left-right instead of top-down. In other words, while displacement increases 100% compare with the inline-4, the second-order vibration increases just 41%. That makes the flat-plane V8 more refined than an inline-4 although it is not as smooth and quiet as cross-plane V8.

To exotic sports cars, less refinement is not a big problem. Especially they usually employ short stroke and light weight pistons / con-rods, the second-order vibration is greatly reduced.

V10 engines

Theoretically, the best V-angle is 72°. Like two inline-5 mated together, there is no vibration in vertical and transverse directions, but there is vibration from end to end of the engine, thus require a balancer shaft install in the V-valley for best balance. However, there is no vibration between bank and bank because pistons in both banks are in the same positions.

V12 engines

Theoretically the best balanced configuration for practical use. It is simply a duplication of inline-6 (therefore achieve the same perfect balance), with corresponding cylinders in both banks joined at the same crank pins. V12 is better than inline-6 just because it has more cylinders, thus doubling the firing frequency and smoothen power delivery.

Of course, the disadvantages are cost, size and weight.

There's no structural differences in crankshaft for all V12s, no matter for luxurious cars or supercars. Most employ 60°, although Ferrari prefers 65°.



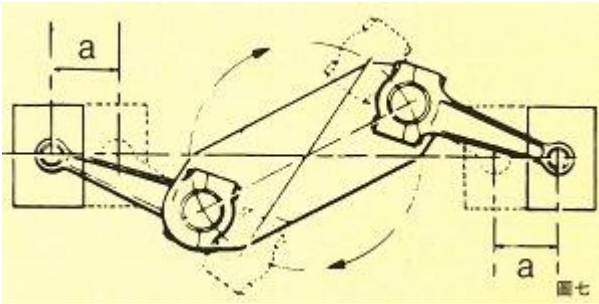
Lamborghini's 60° V12 for Diablo GT



McLaren F1's BMW 60° V12

All horizontally opposed engines (boxer engines)

All boxer engines, regardless of no. of cylinders, provide perfect balance because the movement of a piston is exactly counter by the corresponding piston in another bank.

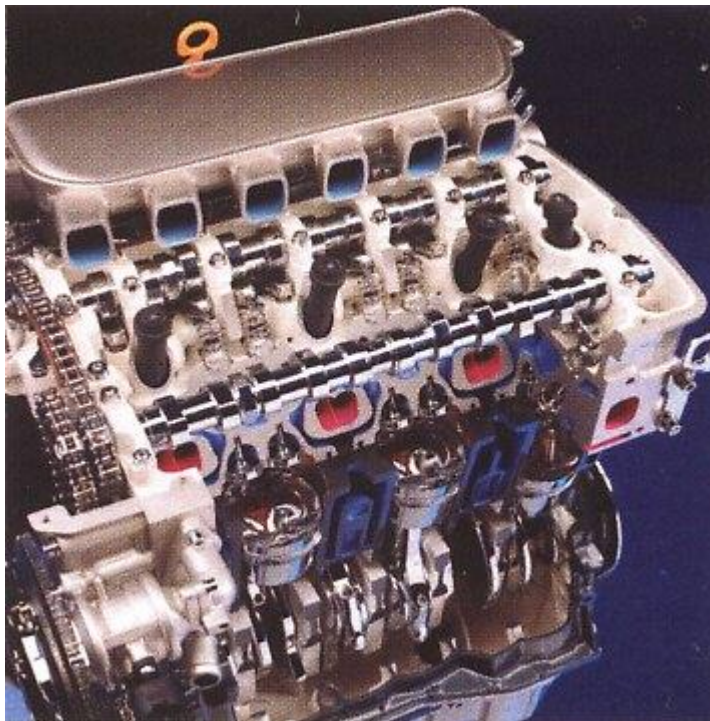


However, they are too wide for good packaging, and is more expensive due to more parts used, thus the usage is limited to Porsche and Subaru today.

Volkswagen VR6, W12 and W16 engines

For conventional V6, a narrow 15° Vee angle would have required extraordinarily large spray angle between split crank pins, hence special strengthening. However, in contrast to many believes, VR6's crankshaft is more like an inline-6. It has 7 main bearings and independent crank throws for each cylinder, (this is possible because VR6 is longer than a conventional V6), thus avoid the crank pin problem.

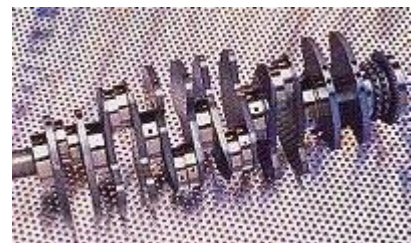
Don't think a 15° V6 must generate a lot of vibration ! on the contrary, the VR6 is inherently a well-balanced configuration because it is nearly identical to an inline-6, just differs from the latter by a very narrow angle separating each pair of 3 cylinders. As a result, it generates no end-to-end vibration like conventional V6s and is actually nearly as smooth as an inline-6.



Cut-away VR6. Note the 7-main bearing crankshaft



W12's cylinder block



W12's crankshaft. Note the slightly split crank pins

If VR6 is a version of inline-6, then W12 must be a version of V12. It is made by mating two VR6 at 72°. The corresponding cylinders in different banks share the same split crank pins. Thanks to the 72° V-angle, the splay angle between split crank pins can be so small that no additional strengthening is required. (see photo) You know, the short engine with 7 main bearings can hardly find space to add strengthened flying webs between the split crank pins.

W16 is identical to W12 except that each bank consists of 4 cylinders instead of 3. In other words, it is made from 2 VR8 engines.



The only mystery left to me is the V5 (formerly called VR5). It's also 15°, but how can it manage to balance between the banks ? one bank has 2 cylinders and another has 3 cylinders. Unfortunately after a lot of time spending, I still fail to find sufficient information about its detailed configuration. If you have its detailed technical specifications or even service manual, please kindly inform me :)

Volkswagen W8 engine

For installing to smaller and lower price cars, W8 is a logical development from the W12. However, W8 does not balance inherently, unlike W12. Like all W engines, the W8 has 5 main bearings and 4 crank throws like a conventional V8. It should have balanced as well as any conventional V8s, but space reason doesn't allow. If you remember, conventional V8s can have 2 configurations:

1) flat-plane V8: some high performance V8s use this configuration. It works like a combination of 2 inline-4 engines so that there is quite a lot of second order vibration generated. However, these engines usually employ short stroke and lightweight pistons / con-rods to enhance power, thus vibration is also largely reduced.

2) Cross-plane V8: most V8s - including all sedans V8s - employ this configuration. It uses large counter balances incorporated in the crank throws to cancel the force generated by pistons and con-rods, thus all vibration is eliminated.

Because W8 is far shorter than conventional V8s, its crank throws are machined extremely thin and have no space for adding large counter balances. As a result, it employs the flat-plane configuration. Therefore W8 does not generate the "rumble bumble" noise like conventional V8s.

On the other hand, being a mass production sedan engine, W8 would have actually generated more vibration than the high performance V8s from Ferrari, Lotus and TVR, because:

1) Long stroke: the narrow-angle configuration does not allow bores too large, otherwise combustion chambers in adjacent banks would have been overlapped. Moreover, a sedan engine requires to generate a health amount of torque. No wonder Passat's 4.0 W8 has a stroke measuring 90.2mm, longer than the bore of 84mm.

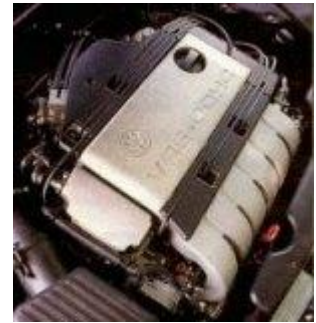
2) Heavier pistons: while Ferrari uses lightweight forged pistons and titanium connecting rods, the W8 can only seek more cost-effective method to cut weight from pistons.

To sports car V8s, a bit vibration means nothing. To the sedan-use W8, the only choice is to add twin-balancer shaft like many inline-4 engines.

Volkswagen's VR6 and W-engines

First generation VR6

6 cylinder engines, no matter in Vee-shape or arranged inline, has superior smoothness against an inline 4-cylinder because all the first order and second order forces can be balanced. However, for most small cars, they don't have the space to accommodate 6-cylinder engines. For space efficiency reason, nearly all small cars employ front-engine + front-wheel-drive

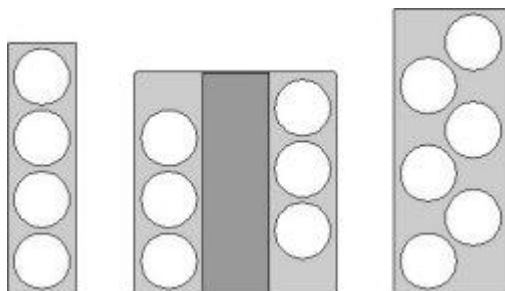


configuration, that is, FF. The engine, clutch, gearbox and differential are all installed up front, accompany with ABS pump, servo, air-conditioning, battery and steering mechanism etc. Therefore it is not easy to fit a six-cylinder engine into the car. Especially is straight-six which is too long for FF because the gearbox and clutch has to be installed right beside it. Even the big Volvo S80 has to specially develop a compact gearbox. V6 could be better because it is very much shorter, at least it can be fitted to Rover 400

Undoubtedly, engines for small cars have to be mounted transversely, unless it is BMW 3-series Compact which has a long long bonnet (hence poor poor space efficiency). But even mounting transversely can't guarantee the installation of a V6. The width of V6 (excluding accessory) is at least doubled from inline-six, depends on the incline angle (usually 60° or 90°), so it engages a lot of length of the engine compartment. Moreover, the hot exhaust pipes in either side of the Vee also prevent any other components from placing too near, thus need more clearance. Therefore most small cars cannot accommodate V6.

In 1991, a breakthrough was achieved by Volkswagen. It developed a narrow-angle (15°) V6 displacing as much as 2.8 litres and installed it to the generation 3 Golf. As everybody knows, this is the so-called "VR6". As seen in the picture, the VR6 is really very compact, nearly as narrow as any inline engine and not much longer than a straight-4. It could be fitted to many small cars, including Polo (which didn't because of price reason). It is also supplied to Mercedes-Benz V-class, whose short front end cannot fit Mercedes' own V6.

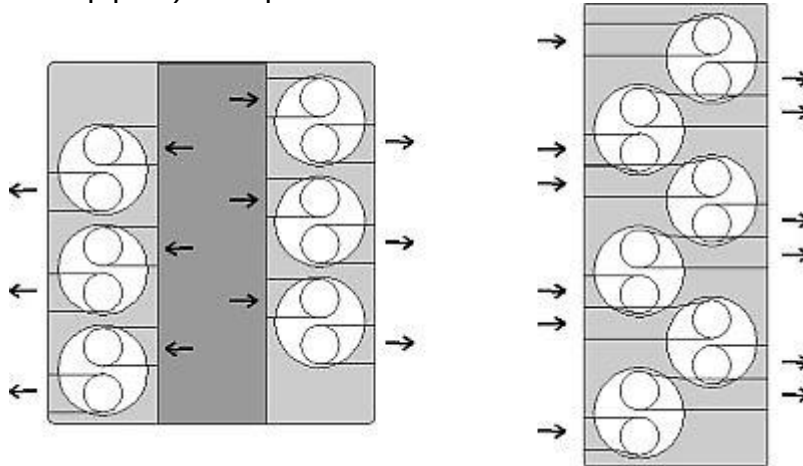
VR6 could be as narrow as 15° without cylinders overlapping is because adjacent cylinders are widely spaced from each other, as seen in the following pictures. This inevitably increase its length but the result is still just equals to 4 and a half cylinder, versus a V6's 3 and a half. For most small cars this is short enough.



Comparison between a straight-4, V6 and a VR6's cylinder block, viewing from above. The V6 has the length equals to 3 and a half cylinder in-line. The VR6 approaches 4 and a half, however, it is a lot narrower.

Asymmetric Configuration

Another feature of VR6 is very important for our further study of 24-valve VR6 and W-engines. It is: the VR6 is asymmetric. For conventional V6, one bank of cylinders mirrors another bank, that means, air intake from the center of the V and exhaust pumps out from outside of the V. (Not vice versa, because the inside of V cannot accommodate the very hot exhaust pipes.) Now please see the illustration in below



Left : Symmetric design of V6

Right : Asymmetric design of

... the VR6 has the air intake from one side and exhaust from another side for ALL cylinders, no matter in which bank, so it is not a symmetric design. Normally, induction manifolds take place at the top of the engine thus waste no space, it is the hot exhaust pipes that engage a lot of space (or length) of the car, especially is a certain clearance should be provided to avoid overheating to surrounding components. Now VR6 concentrate all the exhaust pipes to one side of the engine, thus save space.

The same cannot be implemented to conventional V6s because their adjacent cylinders are packed so close to each other thus provide no space for induction / exhaust pipes running to the same side.

Valve Gear

The first generation VR6 has 2 valves per cylinder, single overhead camshaft (sohc) serving each bank just like any conventional 2-valve V6s, although the 2 camshafts are so close that they look as if a twin-cam design.

Cylinder Head / Block

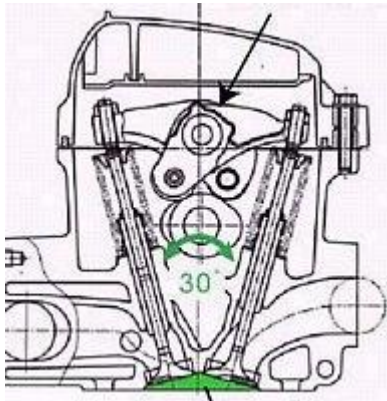
However, in many ways the VR6 is constructed like an in-line engine. Thanks to the narrow angle, the two banks are merged into a single cylinder block. Also, a single cylinder head houses the valve gears for all 6 cylinders. In contrast, a conventional V6 consists of 2 blocks and 2 heads. As a result, VR6 is not only smaller, but also lighter. It would have been cheaper as well if not employ 7-bearing crankshaft.

24-valve VR6

When the whole world is fascinating with 4-valve engines, Volkswagen's VR engine (both VR6 and V5) still relies on sohc 2-valve head until the arrival of the second generation VR6 in July 1999. You may wonder why it takes 8 years to bring the VR6 a 4-valve head. In fact, there was a very big technical difficulty behind the development.

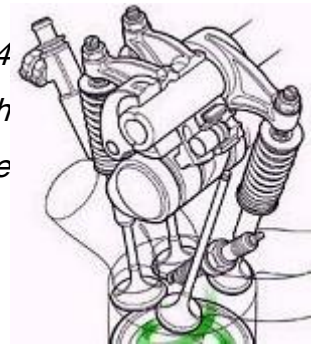
Technical Difficulties

When I heard the rumour about the 24v VR6 about 2 years ago, the first question arose in my mind was: how to fit 4 camshafts into the small piece of cylinder head? It is virtually impossible, especially is that some space has to be preserved for replacing spark plugs. If not having 4 camshafts, then it must be an sohc design serving 4 valves per cylinder, just like many Japanese cars, say, Honda and Mitsubishi.



Honda's SOHC 4-valve engine.

Left : Each camshaft has 4 closely packed cams for each cylinder. The cams activate valves via rocker arms.



Right: the complex rocker arms.

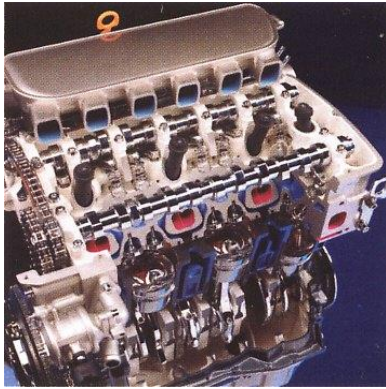
However, sohc 4-valve is not a perfect design. Firstly, it concentrates 3 or 4 elegant, narrow cams to every cylinder, thus relatively complex. Secondly, the most ideal position of a rocker arm / cam set is exactly vertical above the valve it controls. Otherwise the movement may generate a lateral moment which waste power, introduce friction and eventually brings down the rev. For sohc 4-valve, because the ideal position of the rocker arms for intake and exhaust are exactly the same, a small distance shift is introduced to one of them or both of them, thus result in the aforementioned drawback. In fact, all the high performance Honda (from Civic SiR to Type R) employed dohc instead of the sohc of the standard car.

But the most important reason that the sohc 4-valve not desirable is that it doesn't allow the adoption of cam-phasing variable valve timing. Shift the camshaft 20° in advance leads to the intake valves open and close earlier, but so do the exhaust valves. Therefore there is no gain in performance.

Using cam-changing VVT like VTEC or MIVEC may introduce real performance gain, but as already discussed in the [Variable Valve Timing](#) section, it doesn't improve drivability at low speed thus European car makers are not very interested in.

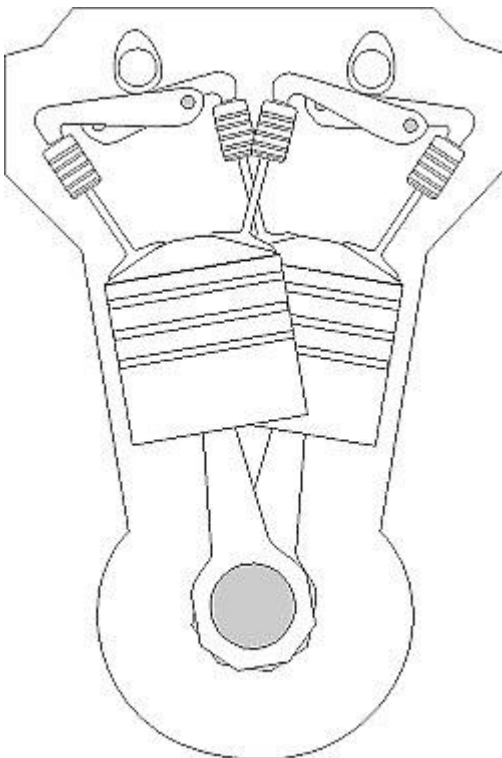
How did Volkswagen overcome these difficulties?

Volkswagen's Solution

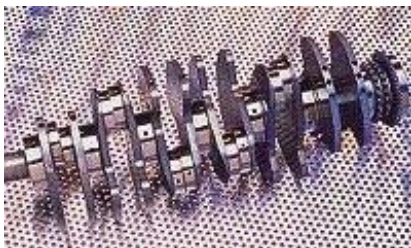


Piech's ingenious engineers solved the problems by introducing a revolutionary concept: Twin-camshaft per bank, one for intake, one for exhaust, but totalled also 2 camshafts. Yes, believe your eyes. Sometimes $2 \times 2 = 2$.

Don't believe ? look at the photo beside. Use a single naked eye to look at the farther camshaft. You'll see the rocker arms pressing valve springs, the direction of springs project to the valves of a cylinder belonging to another bank. If you are not sure, see my illustration in below.



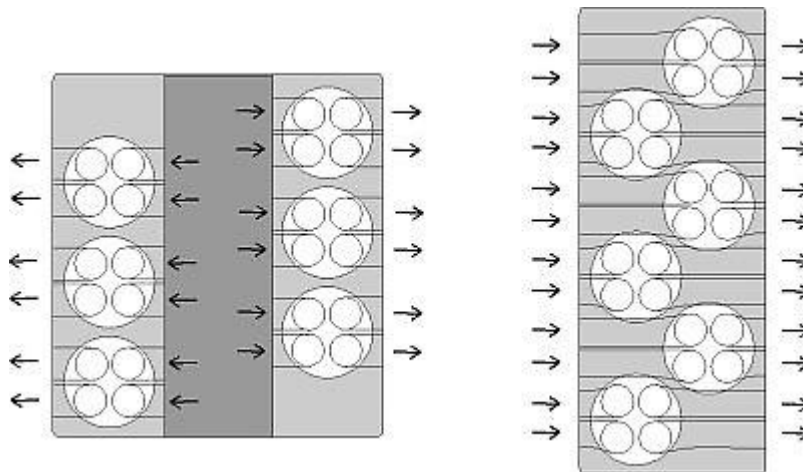
Now it is clear. Camshaft A controls the intake valves of bank A as well as bank B. Similarly, camshaft B controls the exhaust valves in bank B and bank A. In



other words, every cylinder is served by



both camshafts, hence a twin-cam engine. If you still remember, a feature of VR6 is that it is [asymmetric](#), this enable the exhaust valves in both bank remains in a distance accessible by a common camshaft. In fact, the distance is the same as in intake valves / cam set. This ensure equal efficiency of intake and exhaust. Without the narrow angle and the asymmetric configuration, the share of camshaft would have been impossible.



Such design allows cam-phasing variable valve timing to be installed. In the 24-valves VR6, the intake camshaft has VVT. In the future, the exhaust camshaft may also introduce VVT, just like BMW's Double Vanos.

If it were a conventional V6, it would have needed 4 camshafts, 4 cam-phasing mechanism to implement this. Also required is 2 cylinder blocks and 2 cylinder heads. VR6 needs just half of them.

It is also interesting to see the new VR6 has the same no. of camshaft as its 2-valve predecessor. It is one of the most remarkable invention.

W12 engine

Having learned the VR6, it is not difficult to understand the W12. As VW said, the W12 engine shown in the mid-engined W12 supercar is virtually a combination of two VR6s. This is confirmed by its 5.6-litre displacement. It is constructed by mating two 15° VR6 in an inclined angle of 72°. In fact it is the earliest VR engine having 4-valves head, although this car was never put into production.

The W configuration would have been never realised if not the invention of VR6. Audi had been researching its own W-engines for years (even showed in the Avus concept car, but the engine was fake) but eventually pulled out the plug. I remember sources said it failed to solve the exhaust / ventilation problems. It was basically formed by 3 banks of 4-cylinder in-line. The problem was how to run the exhaust pipe for the center bank without overheating the surrounding and without wasting too much space.

It seems that Volkswagen's approach is not benefited by Audi's experience, because the Volkswagen unit is based on the VR6 which was under development well in the 80's. Benefited by VR6's [asymmetric](#) design, exhaust of the left VR6 runs out from the left side, while exhaust of the right VR6 runs out from the right side. Therefore the exhaust system is just the same as any Vee engine.

The only short-coming of W-engines is that they require very thin connecting rods, as the crankshaft is much shorter than V-engines. While VR6 uses con-rods with 20mm

thickness, the W-engines run with 13mm ones. This prevent it from becoming racing engines. Tight cylinder heads may also limit its breathing and ventilation.

W16 engine

Similar to W12, W16 is made by mating two VR8s together, although at the moment Volkswagen group has not shown any VR8. The VR8 consists of 2 banks of 4-cylinder, mated at 15° just like VR6. The two VR8s then join together at 72°. In other words, W16 is just a W12 with one more cylinder added to each bank.



W8 engine

The W8 engine was first introduced in Volkswagen Passat W8. As it is produced in the same production line of other modular family members, the basic architecture is the same as W12 and W16. In other words, it is a W12 with 1 cylinder deleted from each bank, or simply half of a W16. W8 consists of a pair of 15° VR4 engines joint to a common crankshaft at 72°.

W18 engine

As 18 is not dividable by 4, you know the W-18 is not derived from VR engines. In fact, it follows the old Audi philosophy of mating 3 banks of 6-cylinder, running the common crankshaft. The drawback is: among the 3 banks there are 2 large Vee angles. My estimation is 60° each, hence a total of 120°. For comparison, the W16 is just $15/2 + 72 + 15/2 = 87^\circ$, therefore the W-18 is a lot wider. In terms of length, the W16 has the same length as a VR8, that is, about the length of 5 cylinder. The W-18 is as long as an inline-6. As seen in the photo, the W-18 used by Bugatti EB-218 concept car is very big and complex. Two of the banks mate like a conventional 60° V6 while the remaining bank lays down to horizontal level. Complex induction manifolds and exhaust pipes run between the banks. (note that the exhaust pipes were not fitted to this prototype, otherwise it would have looked even more complex.)

Obviously, W-18 is not as clever as W-16. Although there is no problem of fitting in the jumbo Bugatti saloon, I must question its purpose. Is it more powerful than a V12 can achieve ? No. Is it smoother than the theoretically ideal V12 ? No. Is it shorter than a V12 ? No. Is it narrower than a V12 ? On the contrary. Is it cheaper to be built ? Never.

No wonder Volkswagen eventually decided to terminate the W18 project.

Advanced Engine Material

Weight reduction

1. Aluminium head and block

All-aluminium engines (head and block made of aluminium alloy) are increasingly popular. Mass production all-alloy engines such as Rover K-series, BMW M52 straight-six, Nissan VQ-6, Jaguar AJ-V8, Mercedes V6 / V8, GM LS1 and Northstar V8, Peugeot's 2-litre four

and GM's new four-cylinder family proved that aluminium block will spread to nearly all cars in the near future.

Aluminium head has been popular much earlier and most engines now employ it. Car makers favour it not really for weight reduction, but for its better cooling property. As 4-valve head generates more heat than 2-valver, aluminium cylinder head seems to be a good solution.

Block went to aluminium much later, mostly because of cost reason. Block is the heaviest part of the engine, thus using aluminium can save dozens of kilogram and benefit a lot to weight distribution of the car. On the other hand, it is also much more expensive, simply because aluminium is pricier than cast iron.

2. Plastic or Magnesium intake manifolds

Intake manifolds is another heavy component, especially today's variable length manifolds. Using aluminium alloy instead of cast-iron was just the first step. Many car makers now switched to thermoplastic manifolds made of Nylon 66 or other heat-resisting reinforced plastics. It's cheap, light and free-flowing, nearly a dream for car makers.

However, plastic manifold's biggest flaw is noise, which is considered to be too much for luxurious cars. Therefore Mercedes-Benz chose to use Magnesium manifolds. This material is even lighter than aluminium, although a bit dearer and less resistant to heat. No problem, intake manifold is not too hot. Like any metal, air flow in Magnesium pipes generates less noise than plastic one.

TVR's and Ferrari's V8 even employ Kevlar for intake manifolds.

Reduction of friction and inertia

1. Aluminium pistons and cylinder liner (including Nikasil and FRM)

Whether an engine responsive and high-revving depends very much on the inertia of reciprocating parts, i.e., crankshaft, pistons and connecting rods. While crankshaft material is still bounded to steel for the reason of strength, pistons of high-performance engines are usually made of aluminium. The lighter the pistons, the higher rev and power the engine obtains.

Using alloy pistons is not very costly, what prevent most mass production all-alloy engines from using them is the friction generated between pistons and cylinder walls. It is commonly known that the contact between two aluminium surfaces results in high friction - much higher than between cast-iron and aluminium. Therefore many engines with aluminium block have to employ cast iron pistons.

The most common solution is to insert a thin cast-iron liner to the cylinder, covering the cylinder wall and surround the aluminium piston. Of course, this lift production cost at bit.

An alternative solution was introduced by Chevrolet Vega in the mid-70s. Its Cosworth-designed all-alloy engine employed iron-coated aluminium pistons, thus the block could be linerless. However, it's more expensive than cast-iron liner while not delivering as good performance as Nikasil treatment so that no longer in use today.

Instead of cast iron liner, Nikasil treatment coats a layer of Nickel-silicon carbide, usually by electrolytic deposition, to the inner surface of aluminium cylinders. Since Nikasil layer generates even less friction than cast iron liner, revability and power are both enhanced.

Moreover, it is only a few hundreds of a millimetre thick, therefore the spacing between adjacent bores can be reduced considerably, making the engine smaller and lighter. Since the early 70s, Nikasil treatment has been the most favourable solution used by high-performance cars.

The last alternative is fiber-reinforced metal (FRM) cylinder sleeve, which is used by Honda NSX 3.2-litre. Its cost and power / space efficiency are both half way between cast-iron liner and Nikasil. A fiber-based material in the form of cylinder sleeve is first inserted to the die of the block. Melted liquid aluminium is poured into the die and integrate with the fiber sleeve. Then the cylinder wall is machined to the desire bore dimension, leaving only 0.5 mm thickness to the fiber sleeve which covers the cylinder wall. It generates lower friction than iron liner, thus improves rev and power. Moreover, the fiber sleeve reinforces the block, allowing the distance between adjacent bores to be reduced yet maintain mechanical strength.

2. Titanium connecting rods

Everybody knows titanium is light yet strong, although it is very expensive. Finally, this aerospace material spreads to road car use, although still bounded to high-end sports cars. Lamborghini Diablo, Ferrari F355 / 360 M / 550 M etc. and Porsche 911 GT3 use it to raise engine's revability to what would have been impossible.

3. Forged components

Forging seems very old-fashion, but there is still no alternative way to obtain high-strength yet lightweight parts without it. From Honda Type R to all exotic supercars, forged pistons, crankshaft and con-rods are commonly used.

Forging is done completely manually, therefore more human-intensive and expensive. Forge the heated metal into a die result in more homogeneous and closer deposition of metal atoms, thus improved strength and heat-resistivity. With higher strength, the part can be made thinner and lighter, eventually benefiting rev and power.

Braking Systems

Disc Brakes

Drum Brakes

Drum brakes work on the same principle as disc brakes: shoes press against a spinning surface. In this system, that surface is called a drum.

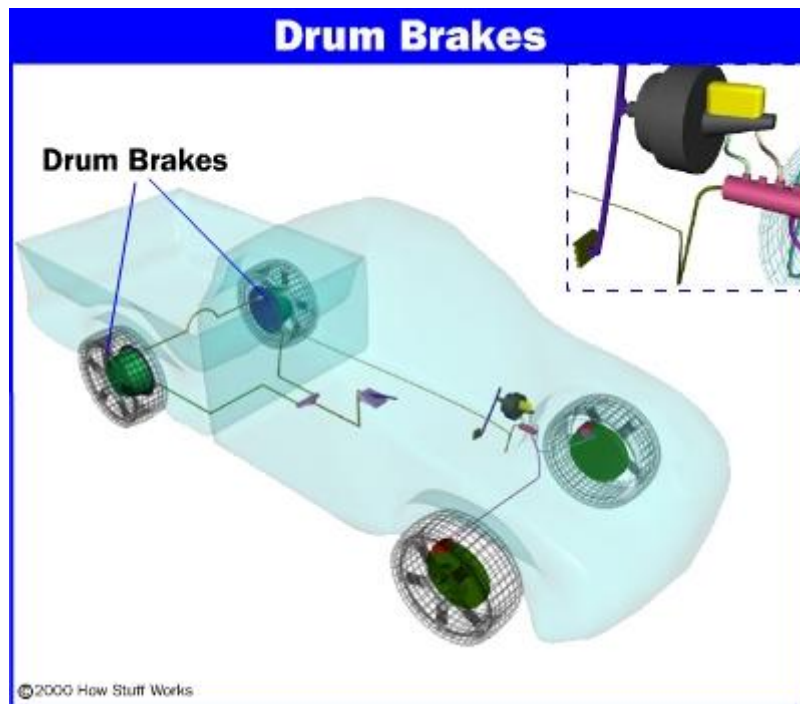


Figure 1. Location of drum brakes

Many cars have drum brakes on the rear wheels and disc brakes on the front. Drum brakes have more parts than disc brakes and are harder to service, but they are less expensive to manufacture, and they easily incorporate an emergency brake mechanism.



Figure 2. Drum brake with drum in place



Figure 3. Drum brake without drum in place

How a Drum Brake Works

The drum brake may look complicated, and it can be pretty intimidating when you open one up, but we can break it down and explain what each piece does.

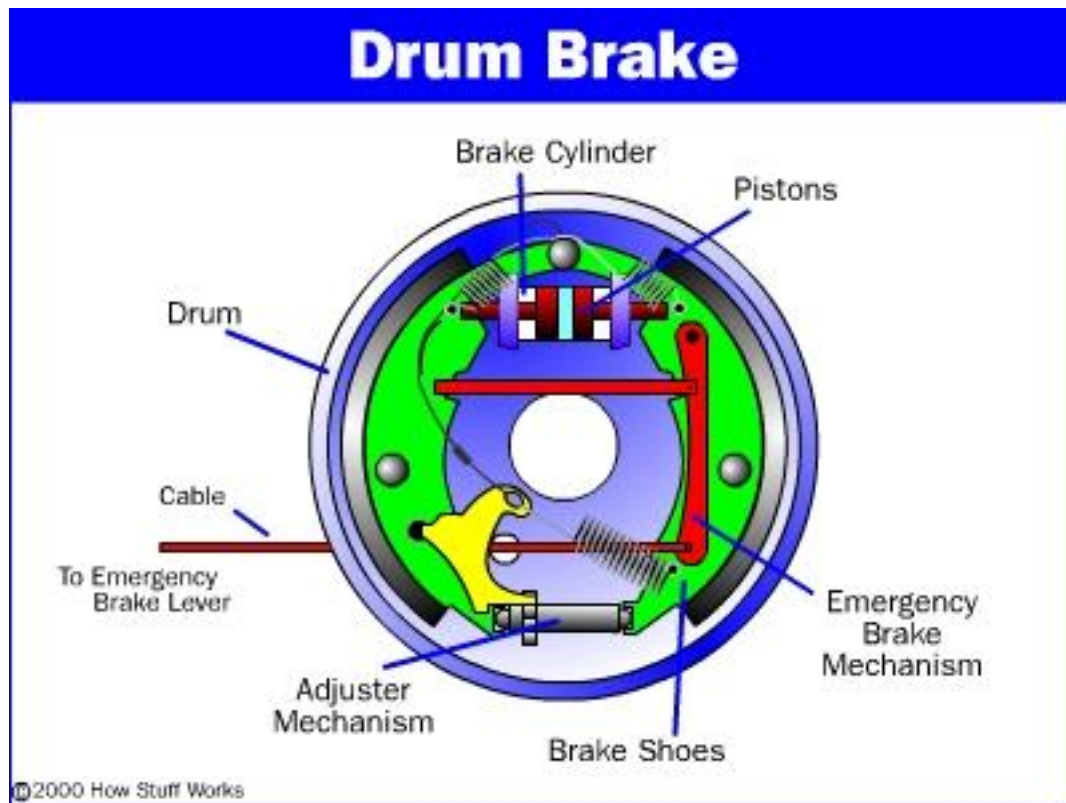


Figure 4. Parts of a drum brake

Like the disc brake, the drum brake has two brake shoes and a piston. But the drum brake also has an adjuster mechanism, an emergency brake mechanism and lots of springs.

When you hit the brake pedal, the piston pushes the brake shoes against the drum. That's pretty straightforward, but why do we need all of those springs?

This is where it gets a little more complicated. Many drum brakes are self-actuating. The extra braking force provided by the wedging action allows drum brakes to use a smaller piston than disc brakes. But, because of the wedging action, the shoes must be pulled away from the drum when the brakes are released. This is the reason for some of the springs. Other springs help hold the brake shoes in place, and return the adjuster arm after it actuates.

How the Brake Adjuster Works

For the drum brakes to function correctly, the brake shoes must remain close to the drum without touching it. If they get too far away from the drum, as the shoes wear down for instance, the piston will require more fluid to travel that distance, and your brake pedal will sink closer to the floor when you apply the brakes. This is why most drum brakes have an automatic adjuster.

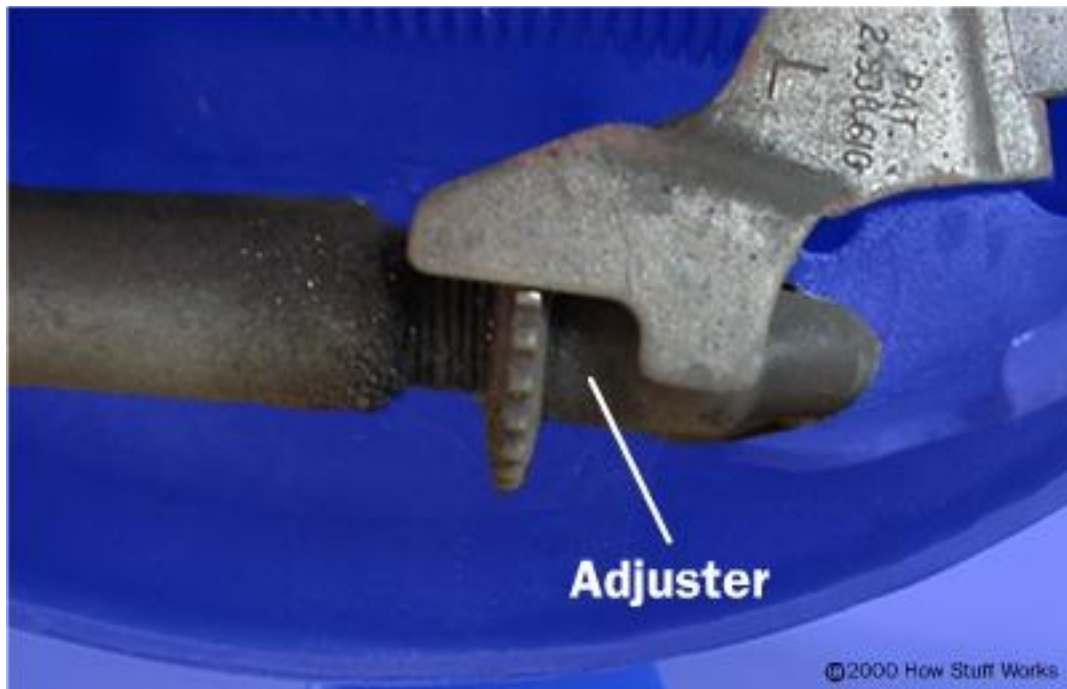


Figure 6. Adjuster mechanism

Now let's add in the parts of the adjuster mechanism. The adjuster uses the self-actuation principle we discussed above.

Each time the car stops while in reverse, the shoe is pulled tight against the drum. When the gap gets big enough, the adjusting lever rocks enough to advance the adjuster gear by one tooth. The adjuster has threads on it, like a bolt, so that it unscrews a little bit when it turns, lengthening to fill in the gap. When the brake shoes wear a little more, the adjuster can advance again, so it always keeps the shoes close to the drum.

Some cars have an adjuster that is actuated when the emergency brake is applied. This type of adjuster can come out of adjustment if the emergency brake is not used for long periods of time. So if you have this type of adjuster, you should apply your emergency brake at least once a week.



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Figure 10. Brake drum

Master Cylinder

To increase safety, most modern car [brake systems](#) are broken into two circuits, with two wheels on each circuit. If a fluid leak occurs in one circuit, only two of the wheels will lose their brakes and your car will still be able to stop when you press the brake pedal.

The **master cylinder** supplies pressure to both circuits of the car. It is a remarkable device that uses two pistons in the same cylinder in such a way as to make the cylinder relatively failsafe. The **combination valve** warns the driver if there is a problem with the brake system, and also does a few more things to make your car safer to drive.

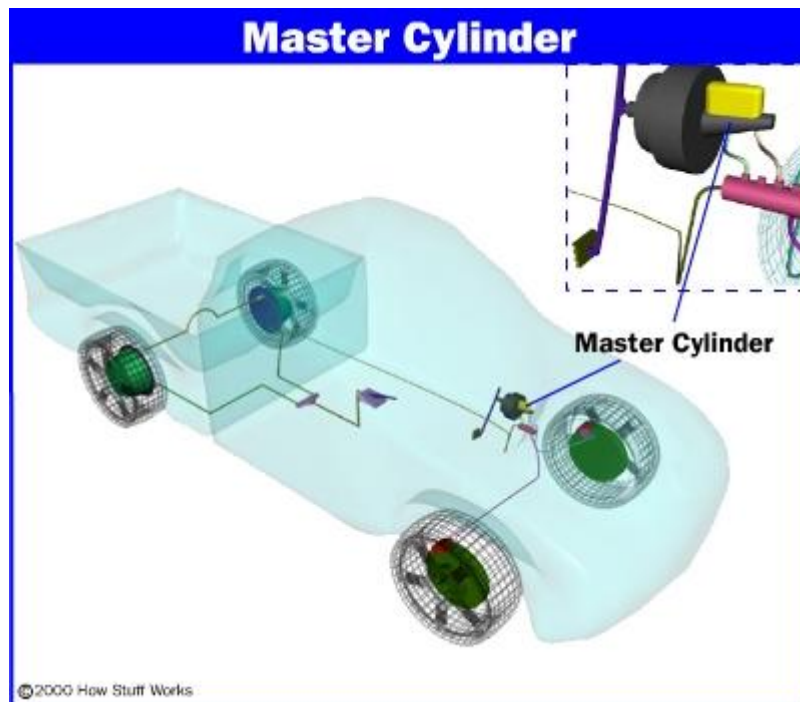


Figure 1. Master cylinder location

Master Cylinder

In **Figures 2**, the plastic tank is the brake fluid reservoir, the master cylinder's brake fluid source. The electrical connection is a sensor that triggers a warning light when the brake fluid gets low.

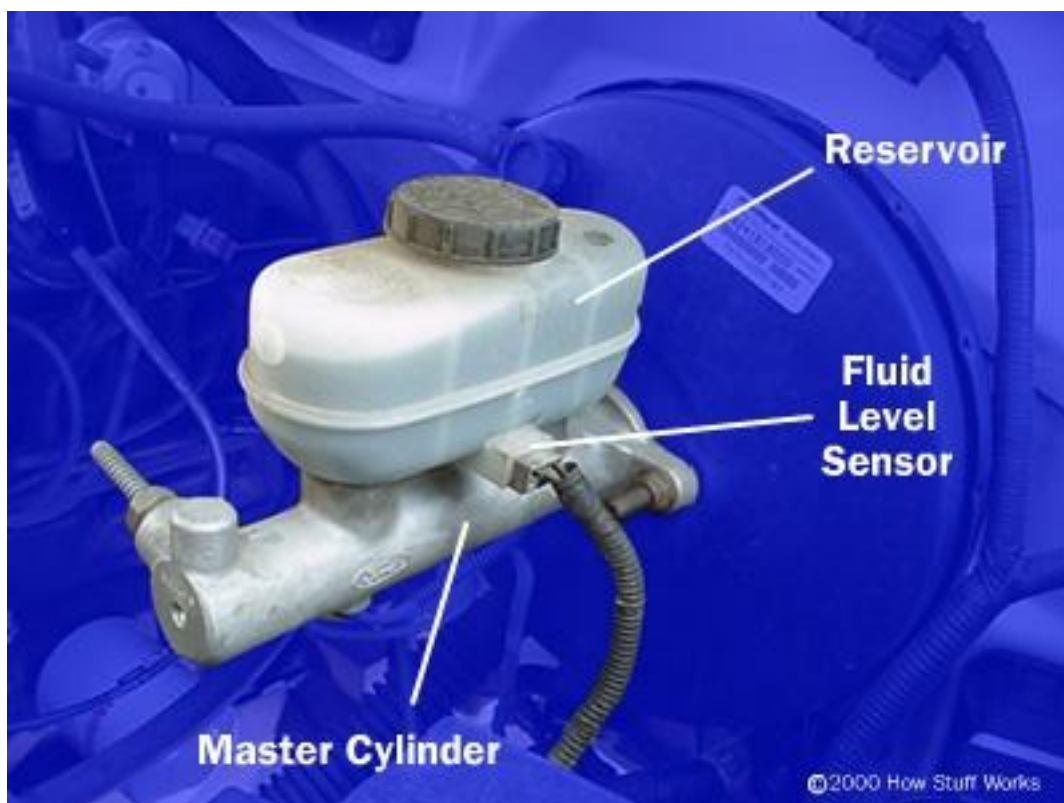


Figure 2. The master cylinder, reservoir and sensor

As **Figure 3** shows, inside the cylinder are two pistons and two springs:

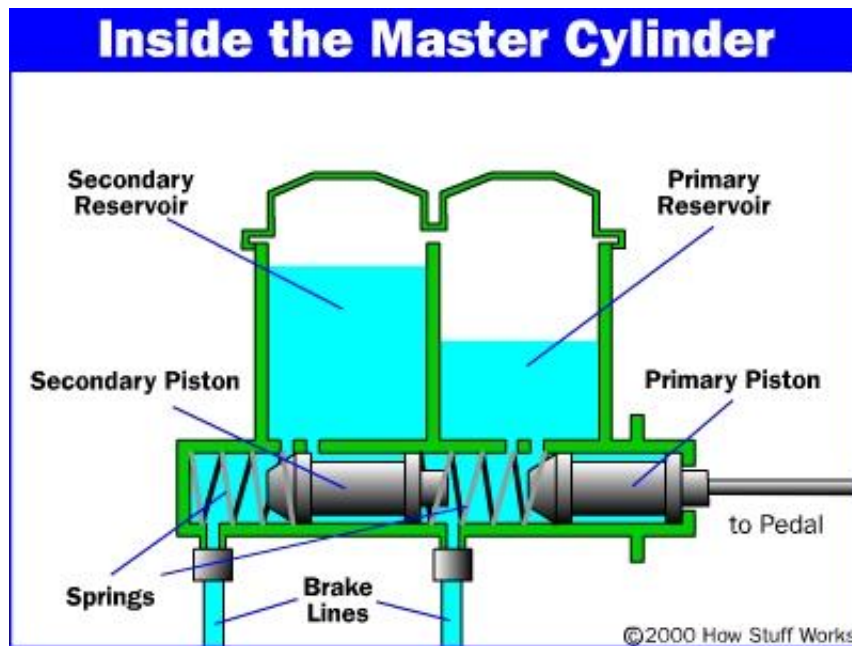


Figure 3. Diagram of master cylinder

When you press the brake pedal, it pushes on the primary piston through a linkage. Pressure builds in the cylinder and lines as the brake pedal is depressed further. The pressure between the primary and secondary piston forces the secondary piston to compress the fluid in its circuit. If the brakes are operating properly, the pressure will be the same in both circuits.

If there is a leak in one of the circuits, that circuit will not be able to maintain pressure. When the first circuit leaks, the pressure between the primary and secondary cylinders is lost; this causes the primary cylinder to contact the secondary cylinder. Now the master cylinder behaves as if it has only one piston. The second circuit will function normally, but you can see from the animation that the driver will have to press the pedal further to activate it. Since only two wheels have pressure, the braking power will be severely reduced.

The Combination Valve

You will find a combination valve on most cars with front-disc and rear-drum brakes, as shown in **Figure 6**. **Figure 7** shows an actual combination valve labeling the three sections.

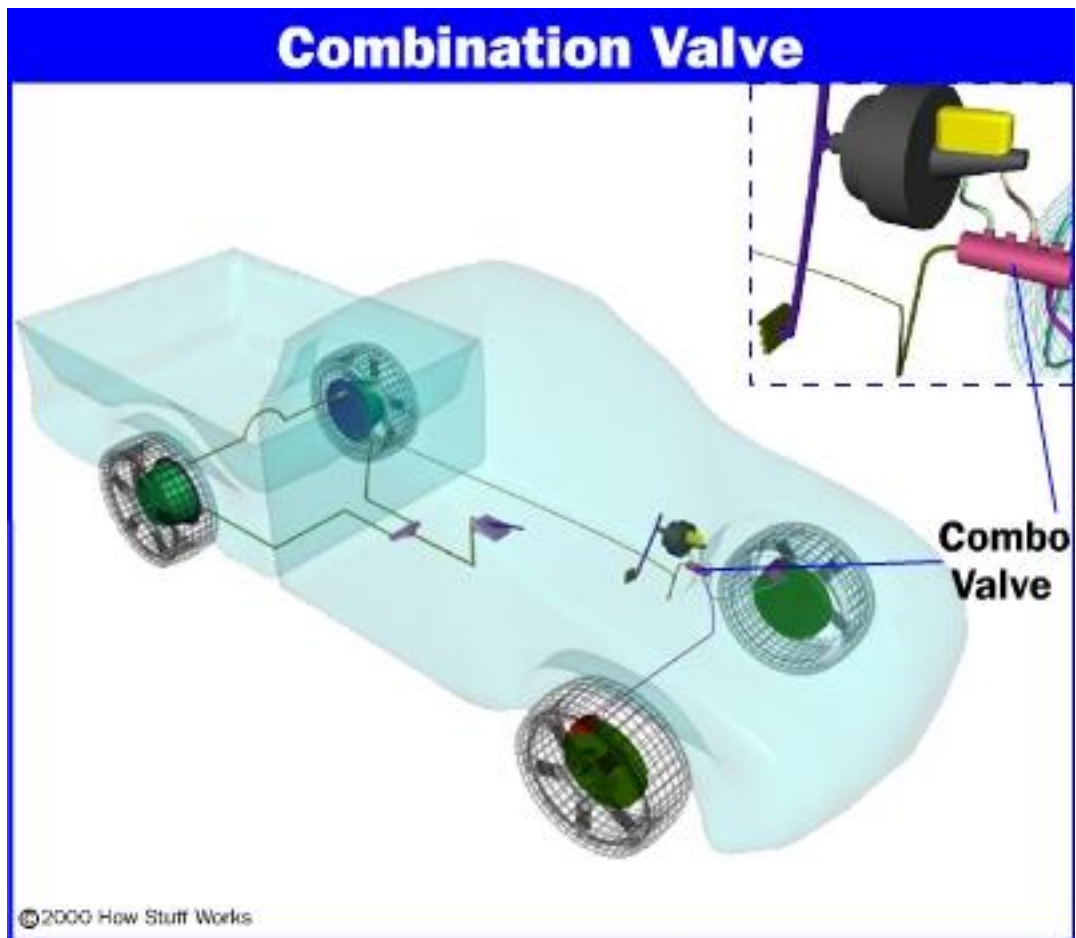


Figure 6. Combination valve location

The valve does the job of three separate devices:

- The metering valve
- The pressure differential switch
- The proportioning valve

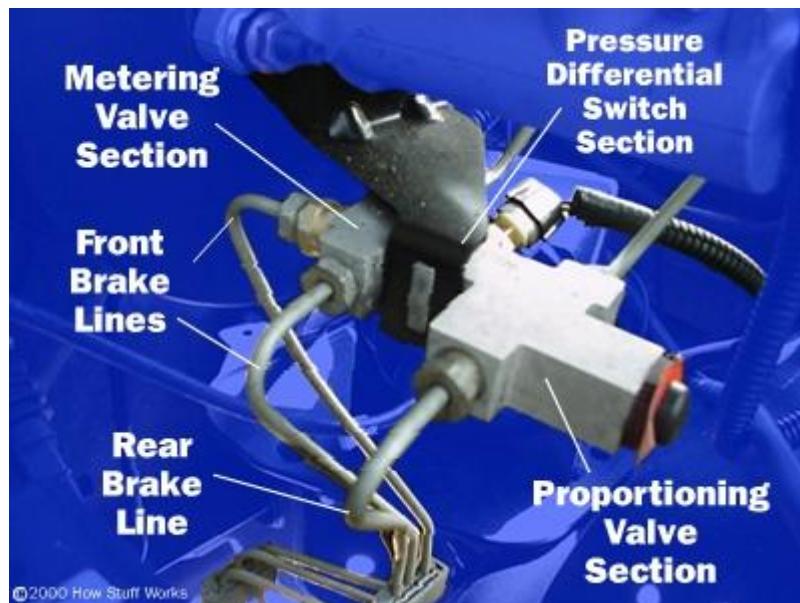


Figure 7. Combination valve sections

The Metering Valve

The metering valve section of the combination valve is required on cars that have disc brakes on the front wheels and drum brakes on the rear wheels. When we look at disc and drum brakes later in this article, we will see that the disc brake pad is normally in contact with the disc, while the drum brake shoes are normally pulled away from the drum. Because of this, the disc brakes are in a position to engage before the drum brakes, when you push the brake pedal down.

The metering valve compensates for this, making the drum brakes engage just before the disc brakes. The metering valve does not allow any pressure to the disc brakes until a threshold pressure has been reached. The threshold pressure is low compared to the maximum pressure in the braking system, so the drum brakes just barely engage before the disc brakes kick in.

Having the rear brakes engage before the front brakes provides a lot more stability during braking. Applying the rear brakes first helps keep the car in a straight line, much like the rudder helps a plane fly straight.

The Pressure Differential Switch

The pressure differential valve is the device that alerts you if you have a leak in one of your brake circuits. The valve contains a specially shaped piston in the middle of a cylinder. Each side of the piston is exposed to the pressure in one of the two brake circuits. As long as the pressure in both circuits is the same, the piston will stay centered in its cylinder. But if one side develops a leak, the pressure will drop in that circuit, forcing the piston off-center. This closes a switch, which turns on a light in the instrument panel of the car. The wires for this switch are visible in Figure 7.

The Proportioning Valve

The proportioning valve reduces the pressure to the rear brakes. Regardless of what type of brakes a car has, the rear brakes require less force than the front brakes.

The amount of brake force that can be applied to a wheel without locking it depends on the amount of weight on the wheel. More weight means more brake force can be applied. If you have ever slammed on your brakes, you know that an abrupt stop makes your car

lean forward. The front gets lower and the back gets higher. This is because a lot of weight is transferred to the front of the car when you stop. Also, most cars have more weight over the front wheels to start with because that is where the engine is located.

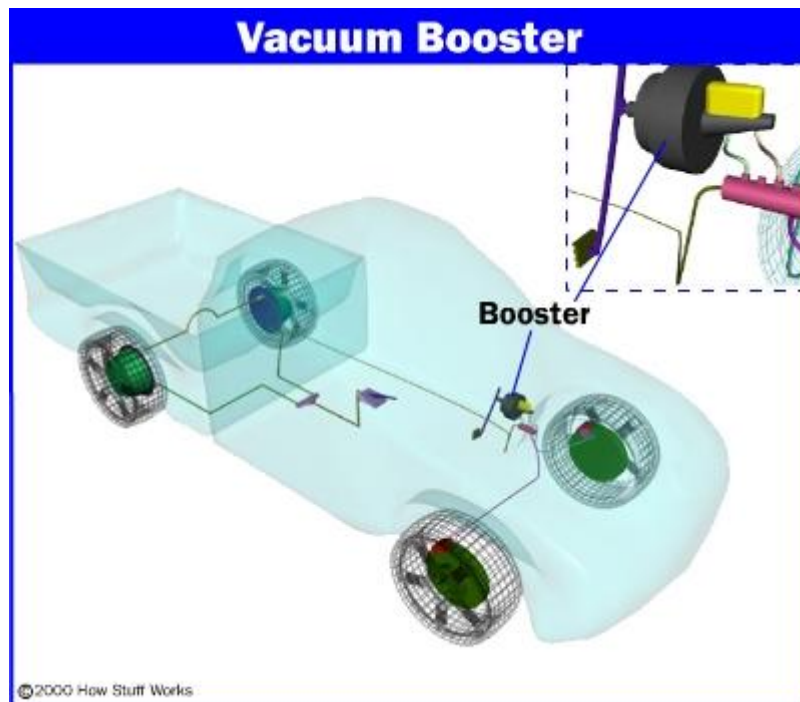
If equal braking force was applied at all four wheels during a stop, the rear wheels would lock up before the front wheels. The proportioning valve only lets a certain portion of the pressure through to the rear wheels so that the front wheels apply more braking force. If the proportioning valve was set to 70% and the brake pressure was 1000 psi for the front brakes, the rear brakes would get 700 psi.

Servo Assisted Braking

If you've ever opened the hood of your car, you've probably seen the brake booster. It's the round, black canister, located at the back of the engine compartment on the driver's side of the car.

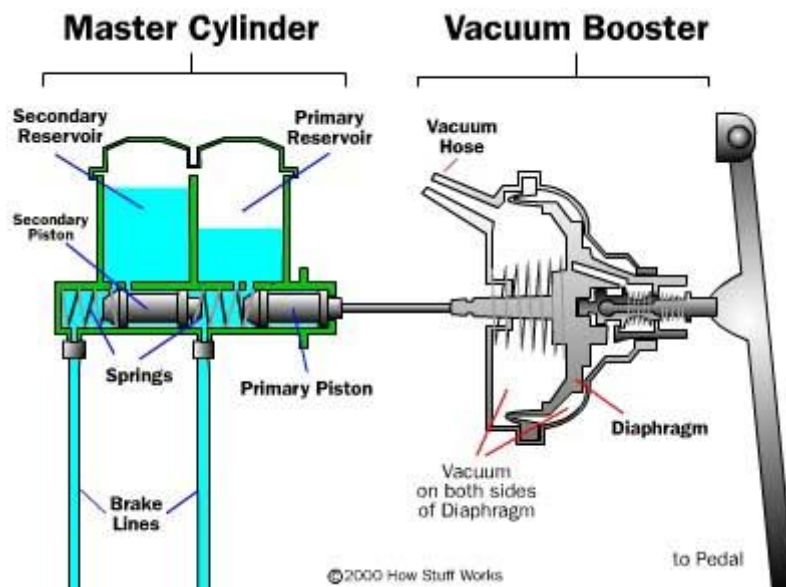


Back in the day, when most cars had drum brakes, power brakes were not really necessary -- [drum brakes](#) naturally provide some of their own power assist. Since most cars today have [disc brakes](#), at least on the front wheels, they need power brakes



The Vacuum Booster

The **vacuum booster** is a metal canister that contains a clever **valve** and a **diaphragm**. A **rod** going through the center of the canister connects to the **master cylinder's piston** on one side and to the **pedal linkage** on the other.



Another key part of the power brakes is the **check valve**.



The photo above shows the check valve, which is a one-way valve that only allows air to be sucked out of the master cylinder. If the engine is turned off, or if a leak forms in a vacuum hose, the check valve makes sure that air does not enter the vacuum booster. This is important because the vacuum booster has to be able to provide enough boost for a driver to make several stops in the event that the engine stops running -- you certainly don't want to lose brake function if you run out of gas on the highway. In the next section, we'll see how the booster works (and check out a cool animation!).

The Booster in Action

The vacuum booster is actually a very simple, elegant design. The device needs a vacuum source to operate. In gasoline-powered cars, the engine provides a vacuum suitable for the boosters. In fact, if you hook a hose to a certain part of an engine, you can suck some of the air out of a container, producing a partial vacuum. Because [diesel engines](#) don't produce a vacuum, diesel-powered vehicles must use a separate vacuum pump.

On cars with a vacuum booster, the brake pedal pushes a rod that passes through the booster into the master cylinder, actuating the master-cylinder piston. The engine creates a partial vacuum inside the vacuum booster on both sides of the diaphragm. When you hit the brake pedal, the rod cracks open a valve, allowing air to enter the booster on one side of the diaphragm while sealing off the vacuum. This increases pressure on that side of the diaphragm so that it helps to push the rod, which in turn pushes the piston in the master cylinder.

As the brake pedal is released, the valve seals off the outside air supply while reopening the vacuum valve. This restores vacuum to both sides of the diaphragm, allowing everything to return to its original position.

Tyres

You've probably been hearing a lot about tires in the news lately. If you own one of the [cars](#) affected by the recent recalls, you may even be shopping for new tires. Because of all

the variables in tire specifications and the confusing jargon you might hear from tire salesmen, this may certainly be a daunting mission. As **Figure 2** illustrates, a tire is made up of several different components.

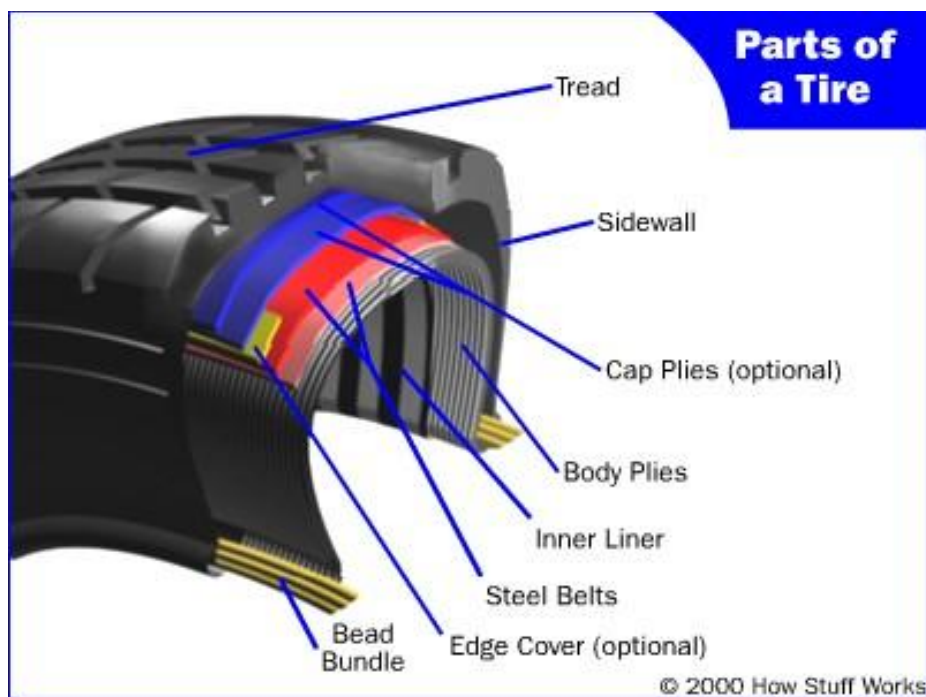


Figure 2. The parts of a tire

The Bead Bundle

The **bead** is a loop of high-strength steel cable coated with rubber. It gives the tire the strength it needs to stay seated on the wheel rim and to handle the forces applied by tire mounting machines when the tires are installed on rims.

The Body

The **body** is made up of several layers of different fabrics, called **plies**. The most common ply fabric is **polyester cord**. The cords in a radial tire run perpendicular to the tread. Some older tires used **diagonal bias tires**, tires in which the fabric ran at an angle to the tread. The plies are coated with rubber to help them bond with the other components and to seal in the air. A tire's strength is often described by the number of plies it has. Most car tires have two body plies. By comparison, large commercial jetliners often have tires with 30 or more plies.

The Belts

In **steel-belted radial** tires, belts made from steel are used to reinforce the area under the tread. These belts provide puncture resistance and help the tire stay flat so that it makes the best contact with the road.

Cap Plies

Some tires have **cap plies**, an extra layer or two of polyester fabric to help hold everything in place. These cap plies are not found on all tires; they are mostly used on tires with higher speed ratings to help all the components stay in place at high speeds.

The Sidewall

The sidewall provides lateral stability for the tire, protects the body plies and helps keep the air from escaping. It may contain additional components to help increase the lateral stability.

The Tread

The **tread** is made from a [mixture](#) of many different kinds of natural and synthetic rubbers. The tread and the sidewalls are extruded and cut to length. The tread is just smooth rubber at this point; it does not have the tread patterns that give the tire **traction**.

Assembly

All of these components are assembled in the tire-building machine. This machine ensures that all of the components are in the correct location and then forms the tire into a shape and size fairly close to its finished dimensions.

At this point the tire has all of its pieces, but it's not held together very tightly, and it doesn't have any markings or tread patterns. This is called a **green tire**. The next step is to run the tire into a **curing machine**, which functions something like a waffle iron, molding in all of the markings and traction patterns. The heat also bonds all of the tire's components together. This is called **vulcanizing**. After a few finishing and inspection procedures, the tire is finished.

Tyre Standard Coding

Tire Type

The **P** designates that the tire is a passenger vehicle tire. Some other designations are **LT** for light truck, and **T** for temporary, or spare tires.

Tire Width

The **235** is the width of the tire in millimeters (mm), measured from sidewall to sidewall. Since this measure is affected by the width of the rim, the measurement is for the tire when it is on its intended rim size.

Aspect Ratio

This number tells you the height of the tire, from the bead to the top of the tread. This is described as a percentage of the tire width. In our example, the aspect ratio is 75, so the tire's height is 75 percent of its width, or 176.25 mm ($.75 \times 235 = 176.25$ mm, or 6.94 in). The smaller the aspect ratio, the wider the tire in relation to its height.

High performance tires usually have a lower aspect ratio than other tires. This is because tires with a lower aspect ratio provide better lateral stability. When a car goes around a turn lateral forces are generated and the tire must resist these forces. Tires with a lower profile have shorter, stiffer sidewalls so they resist cornering forces better.

Tire Construction

The **R** designates that the tire was made using radial construction. This is the most common type of tire construction. Older tires were made using diagonal bias (**D**) or bias

belted (**B**) construction. A separate note indicates how many plies make up the sidewall of the tire and the tread.

Rim Diameter

This number specifies, in inches, the wheel rim diameter the tire is designed for.

Uniform Tire Quality Grading

Passenger car tires also have a grade on them as part of the **uniform tire quality grading** (UTQG) system. Your tire's UTQG rating tells you three things:

- **Tread Wear:** This number comes from testing the tire in controlled conditions on a government test track. The higher the number, the longer you can expect the tread to last. Since no one will drive his or her car on exactly the same surfaces and at the same speeds as the government test track, the number is not an accurate indicator of how long your tread will actually last. It's a good relative measure, however: You can expect a tire with a larger number to last longer than one with a smaller number.
- **Traction:** Tire traction is rated **AA**, **A**, **B** or **C**, with AA at the top of the scale. This rating is based on the tire's ability to stop a car on wet concrete and asphalt. It does not indicate the tire's cornering ability. According to [this NHTSA page](#), the Firestone Wilderness AT and Radial ATX II tires that have been in the news have a traction rating of B.
- **Temperature:** The tire temperature ratings are **A**, **B** or **C**. The rating is a measure of how well the tire dissipates heat and how well it handles the buildup of heat. The temperature grade applies to a properly inflated tire that is not overloaded. Underinflation, overloading or excessive speed can lead to more heat buildup. Excessive heat buildup can cause tires to wear out faster, or could even lead to tire failure.
- **Service Description**
The service description consists of two things:
 - **Load Ratings:** The load rating is a number that correlates to the maximum rated load for that tire. A higher number indicates that the tire has a higher load capacity. The rating "105," for example, corresponds to a load capacity of 2039 pounds (924.87 kg). A separate note on the tire indicates the load rating at a given inflation pressure.
 - **Speed Rating:** The letter that follows the load rating indicates the maximum speed allowable for this tire (as long as the weight is at or below the rated load). For instance, **S** indicates that the tire can handle speeds up to 112 mph (180.246 kph).

Calculating the Tire Diameter

Now that we know what these numbers mean, we can calculate the overall diameter of a tire. We multiply the tire width by the aspect ratio to get the height of the tire.

Tire height = 235 x 75 percent = 176.25 mm (6.94 in)

Then we add twice the tire height to the rim diameter.

2 x 6.94 in + 15 inches = 28.9 in (733.8 mm)

This is the unloaded diameter; as soon as any weight is put on the tire, the diameter will decrease.

Traction

There are a lot of different terms used today in the tire industry. Some of them actually mean something and some do not. In this section, we'll try to explain what some of the terms mean.

All-Season Tires with Mud and Snow Designation

If a tire has **MS**, **M+S**, **M/S** or **M&S** on it, then it meets the [Rubber Manufacturers Association](#) (RMA) guidelines for a mud and snow tire. For a tire to receive the Mud and Snow designation, it must meet these geometric requirements (taken from the bulletin "RMA Snow Tire Definitions for Passenger and Light Truck (LT) Tires"):

1. *New tire treads shall have multiple pockets or slots in at least one tread edge that meet the following dimensional requirements based on mold dimensions:*

- a. Extend toward the tread center at least 1/2 inch from the footprint edge, measured perpendicularly to the tread centerline.*
- b. A minimum cross-sectional width of 1/16 inch.*
- c. Edges of pockets or slots at angles between 35 and 90 degrees from the direction of travel.*

2. *The new tire tread contact surface void area will be a minimum of 25 percent based on mold dimensions.*

The rough translation of this specification is that the tire must have a row of fairly big grooves that start at the edge of the tread and extend toward the center of the tire. Also, at least 25 percent of the surface area must be grooves.

The idea is to give the tread pattern enough void space so that it can bite through the snow and get traction. However, as you can see from the specification, there is no testing involved.

To address this shortcoming, the Rubber Manufacturers Association and the tire industry have agreed on a new standard that does involve testing. The new designation will be called "Severe Snow Use" and will have a new icon (**Figure 6**), which will go next to the M/S designation.



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In order to meet this new standard, tires must be tested using an **Figure 6. New severe** [American Society for Testing and Materials](#) (ASTM) testing winter traction icon.

procedure described in this bulletin, "RMA Definition for Passenger and Light Truck Tires for use in Severe Snow Conditions."

Tires designed for use in severe snow conditions are recognized by manufacturers to attain a traction index equal to or greater than 110 compared to the ASTM E-1136 Standard Reference Test Tire when using the ASTM F-1805 snow traction test with equivalent percentage loads.

These tires, in addition to meeting the geometrical requirements for an M/S designation, are tested on snow using a standardized test procedure. They have to do better than the standard reference tire in order to meet the requirements for Severe Snow Use.

Tires with the snowflake symbol are now available, but full implementation will not occur until the end of 2001. The Oregon Department of Transportation has published a [list](#) of tires that meet the new standard even though they may not bear the new symbol.

Hydroplaning

Hydroplaning can occur when the car drives through puddles of standing water. If the water cannot squirt out from under the tire quickly enough, the tire will lift off the ground and be supported by only the water. Because the affected tire will have almost no traction, cars can easily go out of control when hydroplaning.

Some tires are designed to help reduce the possibility of hydroplaning. These tires have deep grooves running in the same direction as the tread, giving the water an extra channel to escape from under the tire.



Photo courtesy [Goodyear](#)

How Tires Support a Car

You may have wondered how a car tire with 30 pounds per square inch (psi) of pressure can support a car. This is an interesting question, and it is related to several other issues, such as how much force it takes to push a tire down the road and why tires get hot when you drive (and how this can lead to problems).

The next time you get in your car, take a close look at the tires. You will notice that they are not really round. There is a flat spot on the bottom where the tire meets the road. This flat spot is called the **contact patch**.

If you were looking up at a car through a glass road, you could measure the size of the contact patch. You could also make a pretty good estimate of the weight of your car, if you measured the area of the contact patches of each tire, added them together and then multiplied the sum by the tire pressure.

Since there is a certain amount of pressure per square inch in the tire, say 30 psi, then you need quite a few square inches of contact patch to carry the weight of the car. If you add more weight or decrease the pressure, then you need even more square inches of contact patch, so the flat spot gets bigger.



Properly Inflated



Underinflated/
Overloaded

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Figure 9. A properly inflated tire and an underinflated or overloaded tire.

In **Figure 9**, you can see that the underinflated/overloaded tire is less round than the properly inflated, properly loaded tire. When the tire is spinning, the contact patch must move around the tire to stay in contact with the road. You can see in Figure 9 that at the spot where the tire meets the road, the rubber is bent out. It takes force to bend that tire, and the more it has to bend, the more force it takes. The tire is not perfectly elastic, so when it returns to its original shape, it does not return all of the force that it took to bend it. Some of that force is converted to heat in the tire by the friction and work of bending all of the rubber and steel in the tire. Since an underinflated or overloaded tire needs to bend more, it takes more force to push it down the road, so it generates more heat.

Tire manufacturers sometimes publish a **coefficient of rolling friction** (CRF) for their tires. You can use this number to calculate how much force it takes to push a tire down the road. The CRF has nothing to do with how much traction the tire has; it is used to calculate the amount of drag or rolling resistance caused by the tires. The CRF is just like any other [coefficient of friction](#): The force required to overcome the friction is equal to the CRF multiplied by the weight on the tire. This table lists typical CRFs for several different types of wheels.

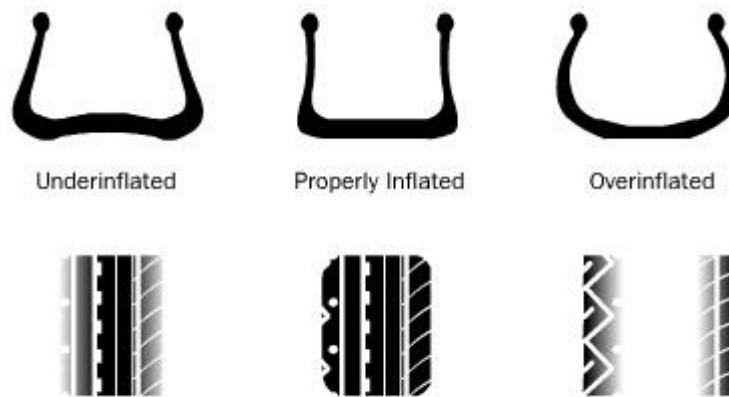
Tire Type	Coefficient of Rolling Friction
Low-Rolling Resistance Car Tire	0.006-0.01
Ordinary Car Tire	0.015
Truck Tire	0.006-0.01
Train Wheel	0.001

Let's figure out how much [force](#) a typical car might use to push its tires down the road. Let's say our car weighs 4,000 pounds (1814.369 kg), and the tires have a CRF of 0.015. The force is equal to $4,000 \times 0.015$, which equals 60 pounds (27.215 kg). Now let's figure out how much [power](#) that is. Power is equal to force times speed. So the amount of power used by the tires depends on how fast the car is going. At 75 mph (120.7 kph), the tires are using 12 horsepower, and at 55 mph (88.513 kph) they use 8.8 horsepower. All of that power is turning into heat. Most of it goes into the tires, but some of it goes into the road (the road actually bends a little when the car drives over it).

From these calculations you can see that the three things that affect how much force it takes to push the tire down the road (and therefore how much heat builds up in the tires) are the weight on the tires, the speed you drive and the CRF (which increases if pressure is decreased).

If you drive on softer surfaces, such as sand, more of the heat goes into the ground, and less goes into the tires, but the CRF goes way up.

Problems With Tires



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Figure 10. The wear patterns of an underinflated, properly inflated and overinflated tire.

Underinflation can cause tires to wear more on the outside than the inside. It also causes reduced fuel efficiency, and increased buildup of heat in the tires. It is important to check the tire pressure with a [gauge](#) at least once a month.

Overinflation causes tires to wear more in the center of the tread. The tire pressure should never exceed the maximum that is listed on the side of the tire. Car manufacturers often suggest a lower pressure than the maximum because the tires will give a softer ride. But running the tires at a higher pressure will improve mileage.

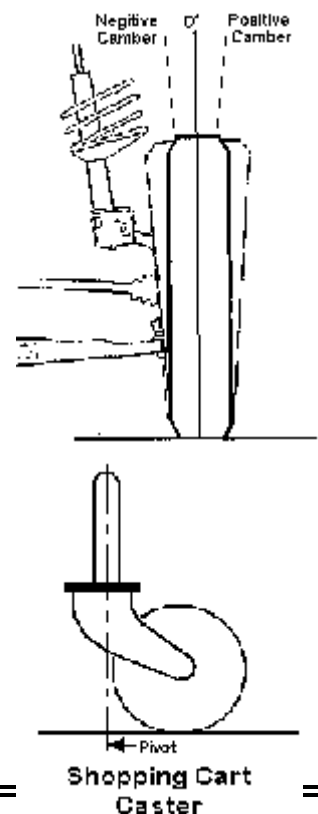
Misalignment of the wheels causes either the inside or the outside to wear unevenly, or to have a rough, slightly torn appearance.

Wheel Alignment

In its most basic form, a wheel alignment consists of adjusting the angles of the wheels so that they are perpendicular to the ground and parallel to each other. The purpose of these adjustments is maximum tire life and a vehicle that tracks straight and true when driving along a straight and level road.

Camber

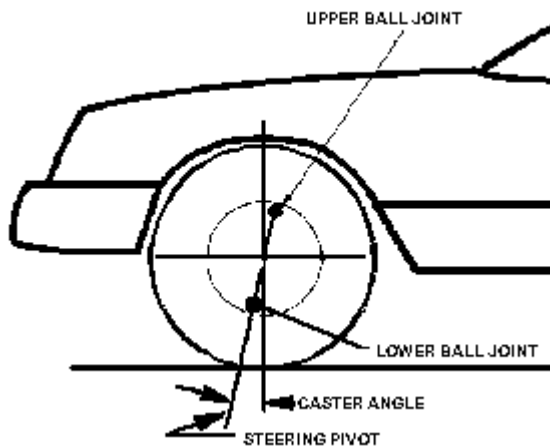
Camber is the angle of the wheel, measured in degrees, when viewed from the front of the vehicle. If the top of the wheel is leaning out from the center of the car, then the camber is positive, if it's leaning in, then the camber is negative. If the camber is out of adjustment, it will cause tire wear on one side of the tire's tread. If the camber is too far negative, for instance, then the tire will wear on the inside of the tread.





Camber wear pattern

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If the camber is different from side to side it can cause a pulling problem. The vehicle will pull to the side with the more positive camber. On many front-wheel-drive vehicles, camber is not adjustable. If the camber is out on these cars, it indicates that something is worn or bent, possibly from an accident and must be repaired or replaced.

Caster

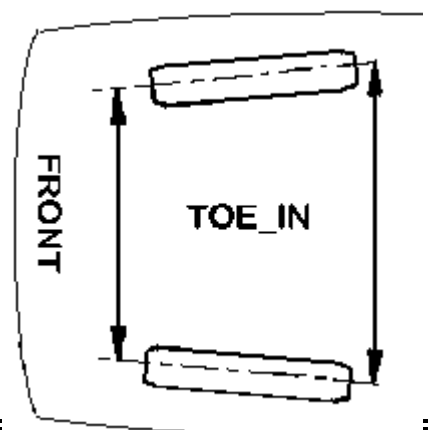
When you turn the steering wheel, the front wheels respond by turning on a pivot attached to the suspension system. Caster is the angle of this steering pivot, measured in degrees, when viewed from the side of the vehicle. If the top of the pivot is

leaning toward the rear of the car, then the caster is positive, if it is leaning toward the front, it is negative. If the caster is out of adjustment, it can cause problems in straight line tracking. If the caster is different from side to side, the vehicle will pull to the side with the less positive caster. If the caster is equal but too negative, the steering will be light and the vehicle will wander and be difficult to keep in a straight line. If the caster is equal but too positive, the steering will be heavy and the steering wheel may kick when you hit a bump. Caster has little affect on tire wear.

The best way to visualize caster is to picture a shopping cart caster. The pivot of this type of caster, while not at an angle, intersects the ground ahead of the wheel contact patch. When the wheel is behind the pivot at the point where it contacts the ground, it is in positive caster. Picture yourself trying to push the cart and keep the wheel ahead of the pivot. The wheel will continually try to turn from straight ahead. That is what happens when a car has the caster set too far negative. Like camber, on many front-wheel-drive vehicles, caster is not adjustable. If the caster is out on these cars, it indicates that something is worn or bent, possibly from an accident, and must be repaired or replaced.

Toe-in

The toe measurement is the difference in the distance between the front of the tires and the back of the tires. It is measured in fractions of an inch in the US and is usually set close to zero which means that the wheels are parallel with each other. Toe-in means that the fronts of the tires are closer to each other than the rears. Toe-out is just the opposite. An incorrect toe-in will cause rapid tire wear to both tires equally. This type of tire wear is called a





sawtooth wear pattern as shown in this illustration.

If the sharp edges of the tread sections are pointing to the center of the car, then there is too much toe-in. If they are pointed to the outside of the car then there is too much toe-out. Toe is always adjustable on the front wheels and on some cars, is also adjustable for the rear wheels.

Four Wheel Alignments

There are two main types of 4-wheel alignments. In each case, the technician will place an instrument on all four wheels. In the first type the rear toe and tracking is checked, but all adjustments are made at the front wheels. This is done on vehicles that do not have adjustments on the rear. The second type is a full 4-wheel alignment where the adjustments are first made to true up the rear alignment, then the front is adjusted. A full 4-wheel alignment will cost more than the other type because there is more work involved.

Other facts every driver should know about wheel alignments.

A wheel alignment should always start and end with a test drive.

The front end and steering linkage should be checked for wear before performing an alignment.

The tires should all be in good shape with even wear patterns.

Pulling problems are not always related to wheel alignment, problems with tires, brakes and power steering can also be responsible. It is up to a good wheel alignment technician to determine the cause.

Advanced Wheel Alignment Information.

While Camber, Caster & Toe-in are the settings that are always checked when doing a wheel alignment, they are not the only settings. Below is a list of the alignment settings that are important for a wheel alignment technician to know about in order to diagnose front end problems.

Camber

When camber specifications are determined during the design stage, a number of factors are taken into account. The engineers account for the fact that wheel alignment specifications used by alignment technicians are for a vehicle that is not moving. On many vehicles, camber changes with different road speeds. This is because aerodynamic forces cause a change in riding height from the height of a vehicle at rest. Because of this, riding height should be checked and problems corrected before setting camber. Camber specs are set so that when a vehicle is at highway speed, the camber is at the optimal setting for minimum tire wear.

For many years the trend has been to set the camber from zero to slightly positive to offset vehicle loading, however the current trend is to slightly negative settings to increase vehicle stability and improve handling.

Caster

Positive caster improves straight line tracking because the caster line (the line drawn through the steering pivot when viewed from the side) intersects the ground ahead of the contact patch of the tire. Just like a shopping cart caster, the wheel is forced behind the pivot allowing the vehicle to track in a straight line.

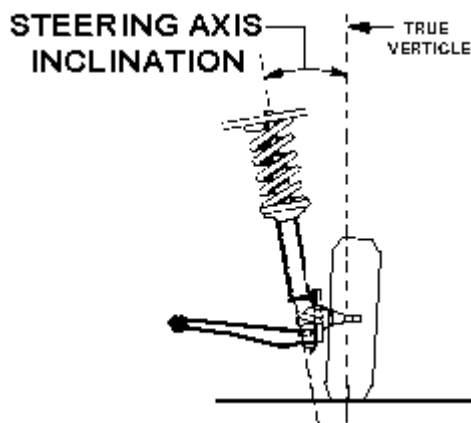
If this is the case, then why did most cars have negative caster specs prior to 1975 ? There are a couple of reasons for this. In those days, people were looking for cars that steered as light as a feather, and cars back then were not equipped with radial tires. Non-radial tires had a tendency to distort at highway speed so that the contact patch moved back past the centerline of the tire (Picture a cartoon car speeding along, the tires are generally drawn as egg-shaped). The contact patch generally moves behind the caster line causing, in effect, a positive caster. This is why, when you put radial tires on this type of car, the car wanders from side to side and no longer tracks straight. To correct this condition, re-adjust the caster to positive and the car should steer like a new car.

Toe

Like camber, toe will change depending on vehicle speed. As aerodynamic forces change the riding height, the toe setting may change due to the geometry of the steering linkage in relation to the geometry of the suspension. Because of this, specifications are determined for a vehicle that is not moving based on the toe being at zero when the vehicle is at

highway speed. In the early days prior to radial tires, extra toe-in was added to compensate for tire drag at highway speed.

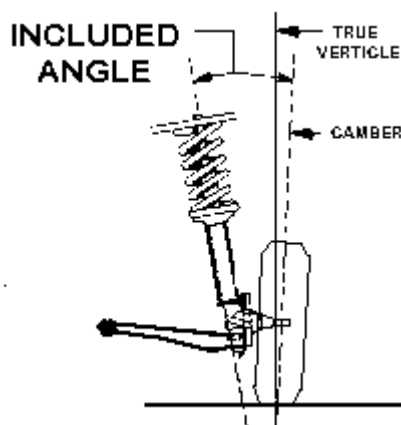
On some older alignment machines, toe-in was measured at each wheel by referencing the opposite wheel. This method caused problems with getting the steering wheel straight the first time and necessitated corrective adjustments before the wheel was straight. Newer machines reference the vehicles centerline by putting instruments on all four wheels. For more information on this see [Steering Center](#) and [Thrust angle](#).



Steering Axis Inclination (SAI)

SAI is the measurement in degrees of the steering pivot line when viewed from the front of the vehicle. This angle, when added to the camber to form the [included angle](#) (see below) causes the vehicle to lift slightly when you turn the wheel away from a straight ahead position. This action uses the weight of the vehicle to cause the steering wheel to return to the center when you let go of it after making a turn. Because of this, if the SAI is different

from side to side, it will cause a pull at very slow speeds. Most alignment machines have a way to measure SAI; however it is not separately adjustable. The most likely cause for SAI being out is bent parts which must be replaced to correct the condition. SAI is also referred to as KPI (King Pin Inclination) on trucks and old cars with king pins instead of ball joints.

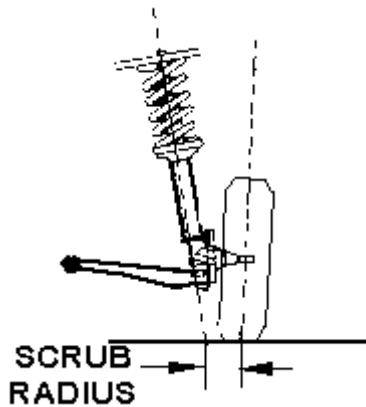


Included Angle

Included angle is the angle formed between the SAI and the camber. Included angle is not directly measurable. To determine the included angle, you

add the SAI to the camber. If the camber is negative, then the included angle will be less

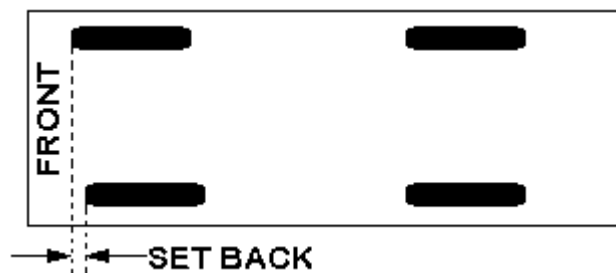
than the SAI, if the camber is positive, it will be greater. The included angle must be the same from side to side even if the camber is different. If it is not the same, then something is bent, most likely the steering knuckle.



Scrub Radius

Scrub radius is the distance between where the SAI intersects the ground and the center of the tire. This distance must be exactly the same from side to side or the vehicle will pull strongly at all speeds. While included angle problems will affect the scrub radius, it is not the only thing that will affect it. Different wheels or tires from side to side will cause differences in scrub radius as well as a tire that is low on air. Positive scrub radius is when the tire contact patch is outside of the SAI pivot, while negative scrub radius is when the

contact patch is inboard of the SAI pivot (front wheel drive vehicles usually have negative scrub radius).



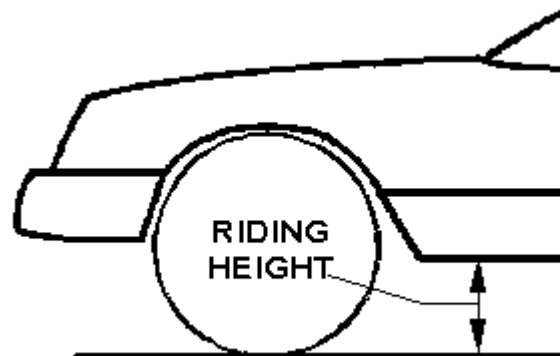
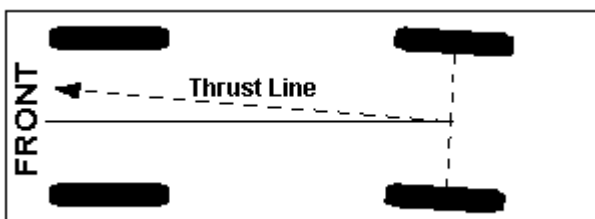
If the brake on one front wheel is not working, with positive scrub radius, stepping on the brake will cause the steering wheel to try to rip out of your hand. Negative scrub radius will minimize that effect.

Scrub radius is designed at the factory and is not adjustable. If you have a vehicle that is pulling even though the alignment is correct, look for something that will affect scrub

radius.

Riding Height

Riding height is measured, usually in inches, from the rocker panel to the ground. Good wheel alignment charts provide specs, but the main thing is that the measurements should be within one inch from side to side and front to rear. Riding height is not adjustable except on vehicles with torsion bar type springs. The best way to fix this problem is to replace the springs (Note: springs should only be replaced in matched pairs). Changes in riding height



will affect camber and toe so if springs are replaced or torsion bars are adjusted, then the wheel alignment must be checked to avoid the possibility of tire wear. It is important to note that the only symptom of

weak coil springs is a sag in the riding height. If the riding height is good, then the springs are good.

Set Back

Set back is when one front wheel is set further back than the other wheel. With alignment equipment that measures toe by using only front instruments, any setback will cause an uncentered steering wheel. Any good 4-aligner will reference the rear wheels when toe in order to eliminate this problem.

the wheel setting Some back is a good chance that something is bent.



good alignment equipment will measure set and give you a reading in inches or millimeters. A set back of less than 1/4 inch considered normal tolerance by some manufacturers. More than that and there is

Thrust Angle

Thrust angle is the direction that the rear wheels are pointing in relation to the center line of the vehicle. If the thrust angle is not zero, then the vehicle will "dog track" and the steering wheel will not be centered. The best solution is to first adjust the rear toe to the center line and then adjust the front toe. This is normally done during a 4-wheel alignment as long as the rear toe is adjustable. If the rear is not adjustable, then the front toe must be set to compensate for the thrust angle, allowing the steering to be centered.

Steering Center

Steering center is simply the fact that the steering wheel is centered when the vehicle is traveling down a straight and level road. A crooked steering wheel is usually the most common complaint that a customer has after a wheel alignment is performed. Assuming that the steering wheel stays in the same position when you let go of the wheel (in other words, the car is not pulling), then steering center is controlled by the front and rear toe settings. When setting steering center, the rear toe should be set first bringing the [Thrust Angle](#) as close to the vehicle centerline as possible. Then the steering wheel is locked in a straight ahead position while the front toe is set. Before locking the steering wheel, the engine should be started and the wheel should be turned right and left a couple of times to take any stress off the power steering valve. After setting the toe, the engine should be started again to be sure that the steering valve wasn't loaded again due to the tie rod adjustments. Of course, you should always road test the vehicle after every alignment as a quality control check.

Another problem with steering center has to do with the type of roads that are driven on. Most roads are crowned to allow for water drainage, and unless you drive in England, Japan or another country where they drive on the ~~wrong~~ (sorry) left side of the road, you usually drive on the right side of the crown. This may cause the vehicle to drift to the right so that the steering wheel will appear to be off-center to the left on a straight road. The best way to compensate for this is as follows:

If there is a difference in caster, it should be that the left wheel is more negative than the right wheel, but not more than 1/2 degree. Check the specs for any specific recommendations on side-to-side differences.

If there is a difference in camber, then the left wheel should be more positive than the right wheel. Check the specs to see what the allowable difference is.

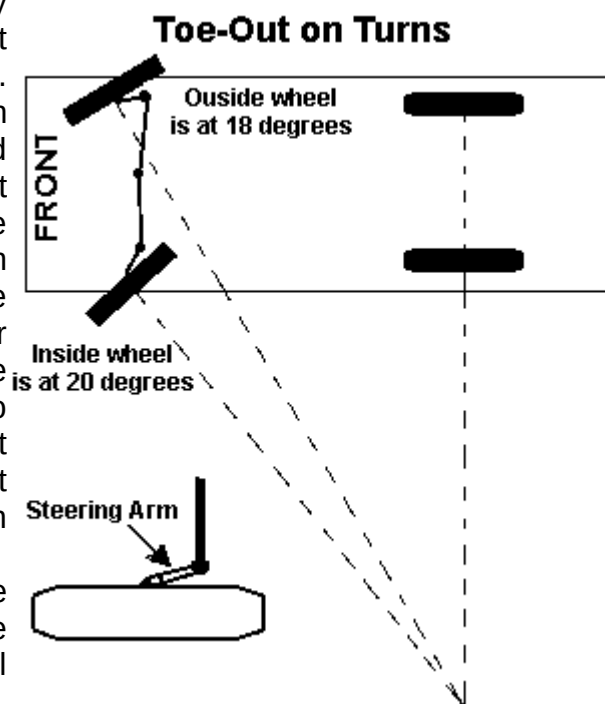
Toe Out on Turns

When you steer a car through a turn, the outside front wheel has to navigate a wider arc than the inside wheel. For this reason, the inside front wheel must steer at a sharper angle than the outside wheel.

Toe-out on turns is measured by angle gauges (turn plates) that every wheel alignment machine. are either directly on the turn are measured electronically and the screen. Wheel alignment specifications will usually provide measurements for toe-out on will give an angle for the inside the outside wheel such as 20° for wheel and 18° for the outside sure that the readings are at zero when the wheels are straight turn the steering wheel so that wheel is at the inside spec. then outside wheel.

The toe-out angles are accomplished by the angle of the This arm allows the inside wheel sharper than the outside wheel.

This arm is either part of the steering knuckle or part of the ball joint and is not adjustable. If there is a problem with the toe-out, it is due to a bent steering arm that must be replaced.

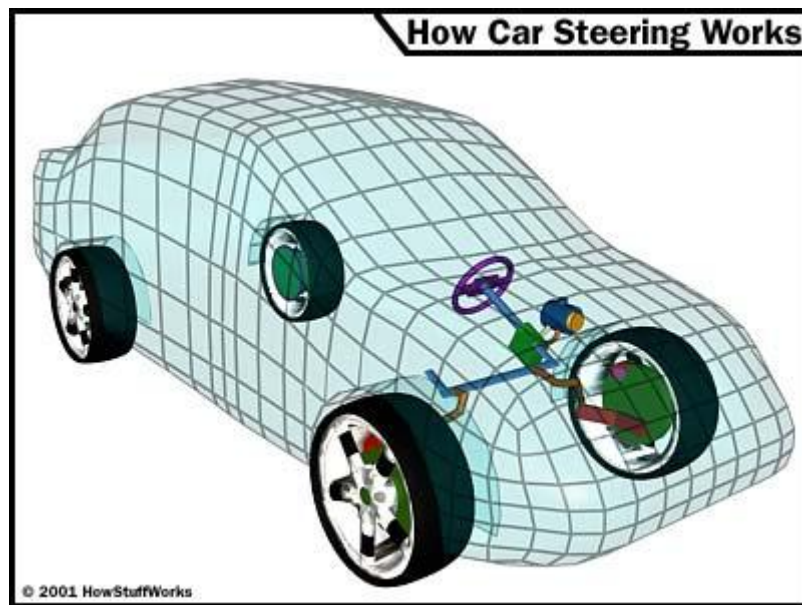


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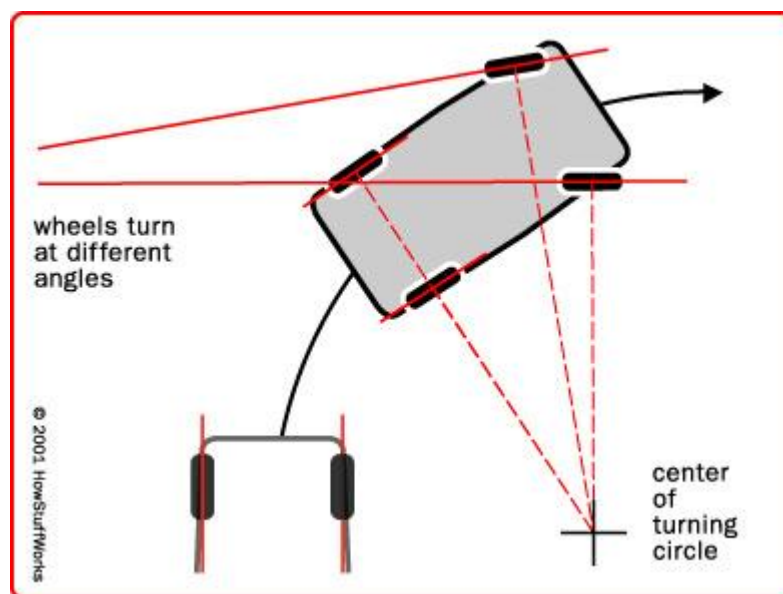
the turns. They wheel and the inside wheel. Make on each side ahead, then the inside check the

steering arm. to turn The steering

Car Steering



You might be surprised to learn that when you turn your car, your front wheels are not pointing in the same direction.

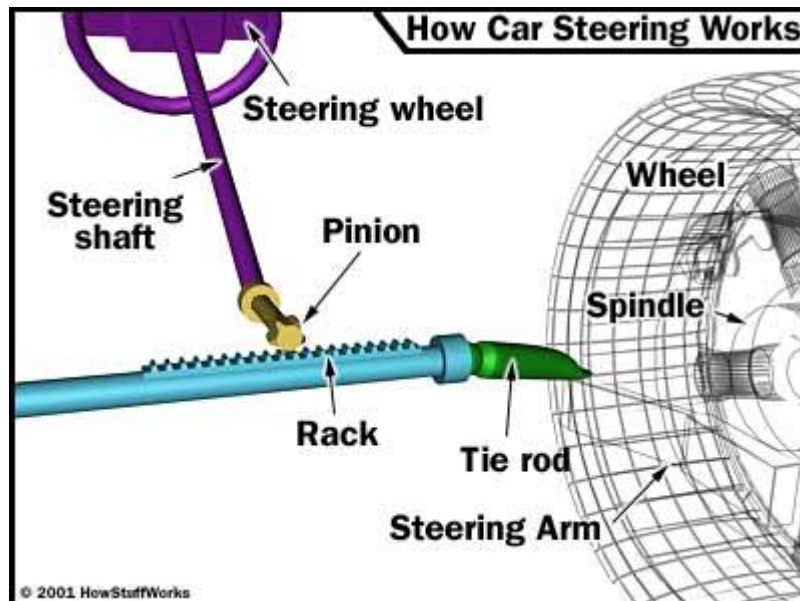


For a car to turn smoothly, each wheel must follow a different circle. Since the inside wheel is following a circle with a smaller radius, it is actually making a tighter turn than the outside wheel. If you draw a line perpendicular to each wheel, the lines will intersect at the center point of the turn..The geometry of the steering linkage makes the inside wheel turn more than the outside wheel. There are a couple different types of steering gears. The most common are **rack-and-pinion** and **recirculating ball**.

Rack-and-pinion Steering

Rack-and-pinion steering is quickly becoming the most common type of steering on cars, small trucks and SUVs. It is actually a pretty simple mechanism. A rack-and-pinion gearset

is enclosed in a metal tube, with each end of the rack protruding from the tube. A rod, called a **tie rod**, connects to each end of the rack.



The **pinion gear** is attached to the **steering shaft**. When you turn the steering wheel, the gear spins, moving the rack. The tie rod at each end of the rack connects to the **steering arm** on the **spindle** (see diagram above).

The rack-and-pinion gearset does two things:

- It converts the rotational motion of the steering wheel into the linear motion needed to turn the wheels.
- It provides a gear reduction, making it easier to turn the wheels.

On most cars, it takes three to four complete revolutions of the steering wheel to make the wheels turn from lock to lock (from far left to far right).

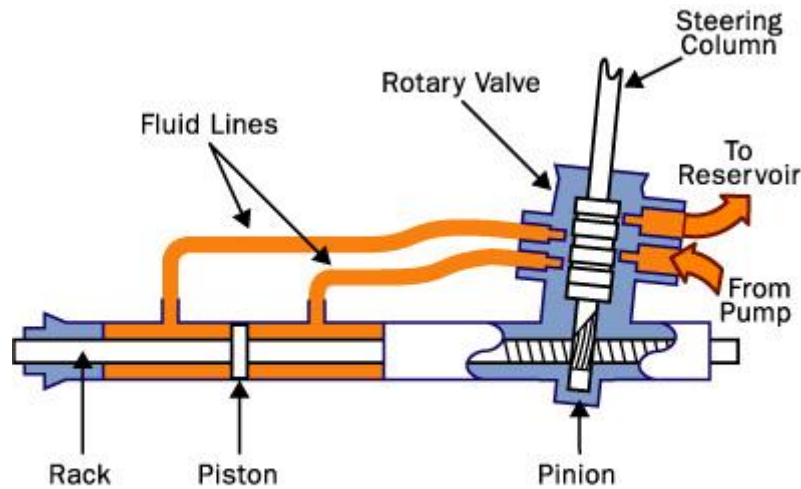
The **steering ratio** is the ratio of how far you turn the steering wheel to how far the wheels turn. For instance, if one complete revolution (360 degrees) of the steering wheel results in the wheels of the car turning 20 degrees, then the steering ratio is 360 divided by 20, or 18:1. A higher ratio means that you have to turn the steering wheel more to get the wheels to turn a given distance. However, less effort is required because of the higher [gear ratio](#).

Generally, lighter, sportier cars have lower steering ratios than larger cars and trucks. The lower ratio gives the steering a quicker response -- you don't have to turn the steering wheel as much to get the wheels to turn a given distance -- which is a desirable trait in sports cars. These smaller cars are light enough that even with the lower ratio, the effort required to turn the steering wheel is not excessive.

Some cars have **variable-ratio steering**, which uses a rack-and-pinion gearset that has a different tooth pitch (number of teeth per inch) in the center than it has on the outside. This makes the car respond quickly when starting a turn (the rack is near the center), and also reduces effort near the wheel's turning limits.

Power Rack-and-pinion

When the rack-and-pinion is in a power-steering system, the rack has a slightly different design.



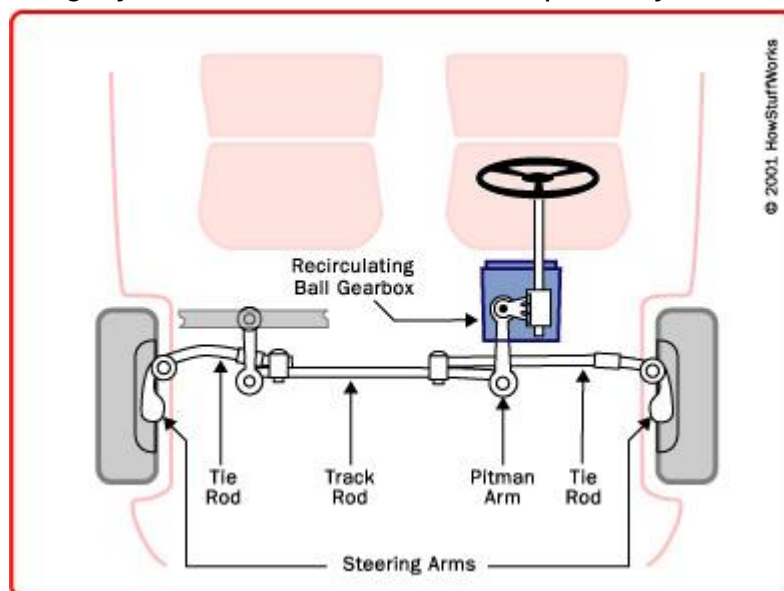
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Part of the rack contains a cylinder with a piston in the middle. The piston is connected to the rack. There are two fluid ports, one on either side of the piston. Supplying higher-pressure fluid to one side of the piston forces the piston to move, which in turn moves the rack, providing the power assist.

We'll check out the components that provide the high-pressure fluid, as well as decide which side of the rack to supply it to, later in the article. First, let's take a look at another type of steering.

Recirculating-ball Steering

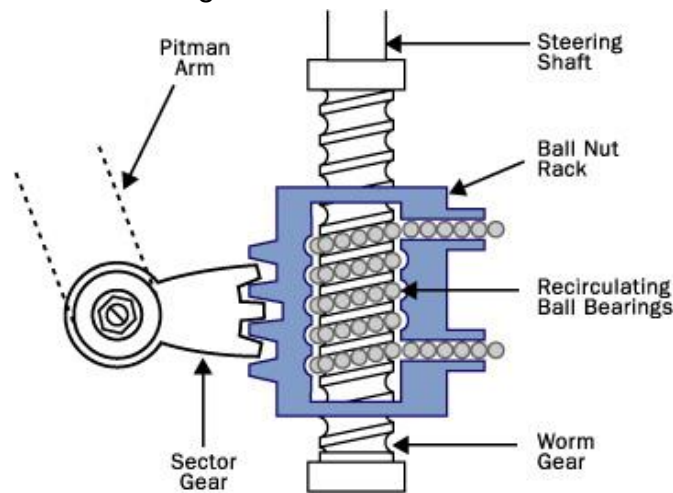
Recirculating-ball steering is used on many trucks and SUVs today. The linkage that turns the wheels is slightly different than on a rack-and-pinion system.



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The recirculating-ball steering gear contains a [worm gear](#). You can image the gear in two parts. The first part is a block of metal with a threaded hole in it. This block has gear teeth cut into the outside of it, which engage a gear that moves the **pitman arm** (see diagram

above). The steering wheel connects to a threaded rod, similar to a bolt, that sticks into the hole in the block. When the steering wheel turns, it turns the bolt. Instead of twisting further into the block the way a regular bolt would, this bolt is held fixed so that when it spins, it moves the block, which moves the gear that turns the wheels.



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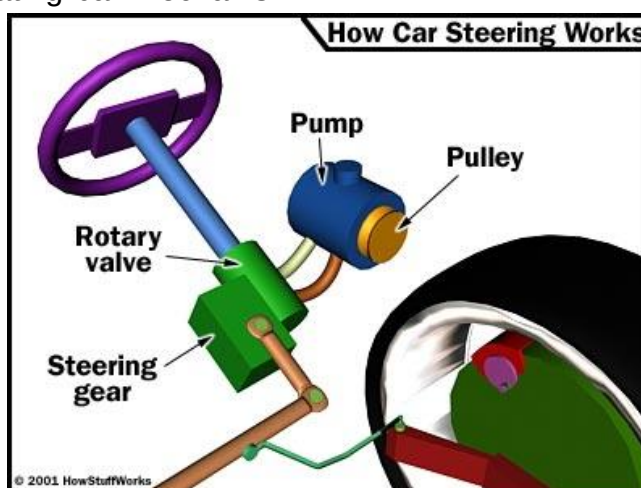
Instead of the bolt directly engaging the threads in the block, all of the threads are filled with [ball bearings](#) that recirculate through the gear as it turns. The balls actually serve two purposes: First, they reduce friction and wear in the gear; second, they reduce **slop** in the gear. Slop would be felt when you change the direction of the steering wheel -- without the balls in the steering gear, the teeth would come out of contact with each other for a moment, making the steering wheel feel loose.

Power steering in a recirculating-ball system works similarly to a rack-and-pinion system. Assist is provided by supplying higher-pressure fluid to one side of the block.

Now let's take a look at the other components that make up a power-steering system.

Power Steering

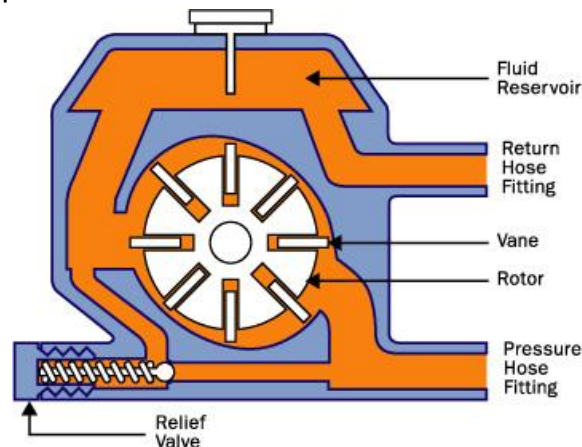
There are a couple of key components in **power steering** in addition to the rack-and-pinion or recirculating-ball mechanism.



Pump

The hydraulic power for the steering is provided by a **rotary-vane pump** (see diagram

below). This pump is driven by the car's engine via a belt and pulley. It contains a set of retractable vanes that spin inside an oval chamber.



As the vanes spin, they pull hydraulic fluid from the return line at low pressure and force it into the outlet at high pressure. The amount of flow provided by the pump depends on the car's engine speed. The pump must be designed to provide adequate flow when the engine is idling. As a result, the pump moves much more fluid than necessary when the engine is running at faster speeds.

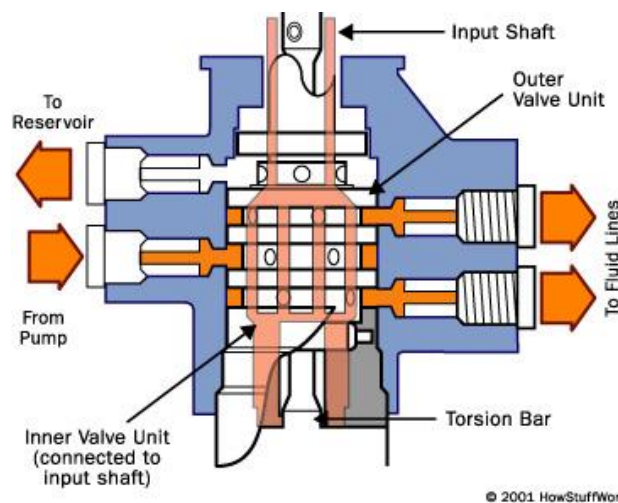
The pump contains a pressure-relief valve to make sure that the pressure does not get too high, especially at high engine speeds when so much fluid is being pumped.

Rotary

Valve

A power-steering system should assist the driver only when he is exerting force on the steering wheel (such as when starting a turn). When the driver is not exerting force (such as when driving in a straight line), the system shouldn't provide any assist. The device that senses the force on the steering wheel is called the **rotary valve**.

The key to the rotary valve is a **torsion bar**. The torsion bar is a thin rod of metal that twists when torque is applied to it. The top of the bar is connected to the steering wheel, and the bottom of the bar is connected to the pinion or worm gear (which turns the wheels), so the amount of torque in the torsion bar is equal to the amount of torque the driver is using to turn the wheels. The more torque the driver uses to turn the wheels, the more the bar twists.



The input from the steering shaft forms the inner part of a **spool-valve assembly**. It also connects to the top end of the **torsion bar**. The bottom of the torsion bar connects to the outer part of the spool valve. The torsion bar also turns the output of the steering gear, connecting to either the pinion gear or the worm gear depending on which type of steering the car has.

As the bar twists, it rotates the inside of the spool valve relative to the outside. Since the inner part of the spool valve is also connected to the steering shaft (and therefore to the steering wheel), the amount of rotation between the inner and outer parts of the spool valve depends on how much torque the driver applies to the steering wheel.

When the steering wheel is not being turned, both hydraulic lines provide the same amount of pressure to the steering gear. But if the spool valve is turned one way or the other, ports open up to provide high-pressure fluid to the appropriate line. It turns out that this type of power-steering system is pretty inefficient. Let's take a look at some advances we'll see in coming years that will help improve efficiency.

The Future of Power Steering

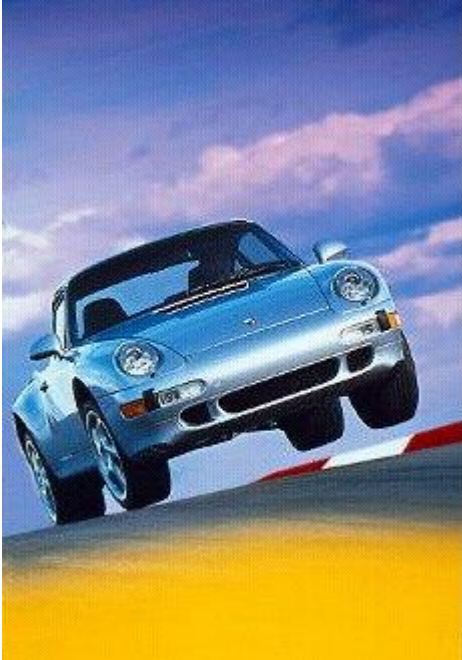
Since the power-steering pump on most cars today runs constantly, pumping fluid all the time, it wastes [horsepower](#). This wasted power translates into wasted fuel.

You can expect to see several innovations that will improve fuel economy:

- **Variable-displacement power-steering pump** - Some cars already utilize this pump. It reduces the volume of fluid being pumped (thereby reducing the power being used) at higher speeds and when the power steering is not needed.
- **Electro-hydraulic systems** - The next step would be to use an [electric motor](#) to power the steering pump. The speed of the motor can be varied, or the motor can be turned off altogether, to reduce the power consumption.
- **Electric power steering** - The next step would be eliminating the hydraulics. An electric motor, mounted to the rack, for example, would assist the steering wheel. Sensors on the steering wheel would tell a control system what the driver is doing, and the electric motor would provide assistance accordingly.
- **Steer-by-wire systems** - Going one step further, these systems would completely eliminate the mechanical connection between the steering wheel and the steering, replacing it with a purely electronic control system. Essentially, the steering wheel would work like the one you can buy for your home computer to play games. It would contain sensors that tell the car what the driver is doing with the wheel, and have some motors in it to provide the driver with feedback on what the car is doing. The output of these sensors would be used to control a motorized steering system. This would free up space in the engine compartment by eliminating the steering shaft. It would also reduce vibration inside the car.

In the past fifty years, car steering systems haven't changed much. But in the next decade, we'll see advances in car steering that will result in more efficient cars and a more comfortable ride.

Handling



Great-handling cars often possess the following features:

- mid-engined
- 4-wheel-drive, or at least RWD
- front to rear weight distribution close to 50/50
- low center of gravity
- lightweight
- a rigid chassis
- sufficient downforce, or at least minimum aerodynamic lift.
- preferably double-wishbones suspensions

Handling is perhaps the most complicated yet most interesting aspect of cars. To optimize handling, engineers have to involve many areas - chassis, suspensions, weight distribution, transmission system, steering, tyres and aerodynamics. On the other hand, they have to compromise with other requirements about packaging, cost and practicality. Even though the design seems perfect, the car has to be tested extensively on different kinds of roads and weather, under different driving style, then progressively tune to deliver desirable result.

What is handling ? Well, let me ask you in this way, how do we comment a car's handling as good ?

In my opinion, good handling means the combination of two things :

1) High cornering speed - that means the car generates a lot of grip in corner, and use the grip optimally such that it can corner at very high g-force. However, this does not equals to Car and Driver's skidpad test result. We need high cornering speed under dynamic conditions, no matter under braking or acceleration, the car is changing direction or not, in various kind of corners and surfaces, not only the tidy 300-foot test ground.

2) Adequate steering - It is not necessarily "neutral", because sometimes we need oversteer and understeer. The steering should be responsive, well weighted and have sufficient feedback.

Then we are going to explore in these 2 directions.



Cornering Speed

1) Tire's Grip

Most obviously, the selection of tyres is decisive to cornering grip. Car engineers have nothing to do with the friction of the tyres, which is determined by the compound and texture. However, they can choose the most suitable tyres for their cars.

In the past decade, increasing tire's diameter and width is a common trend shared by all car makers. Do you still remember the Lamborghini Countach employed 15-inch tyres ? Today's most exotic Ferrari, Porsche and Viper have 18 to 19-inch rubbers ! Larger diameter accompany with larger width increase the contact patch area (that is, the area of the tyre contacts with the ground), thus result in more grip. However, this also result in poorer wet road grip because the pressure acting upon the contact patch (that is, the car's weight divided by contact patch area) is reduced thus the tire becomes easier to "float" on the water. Therefore the texture also need to be improved for better water clearance.

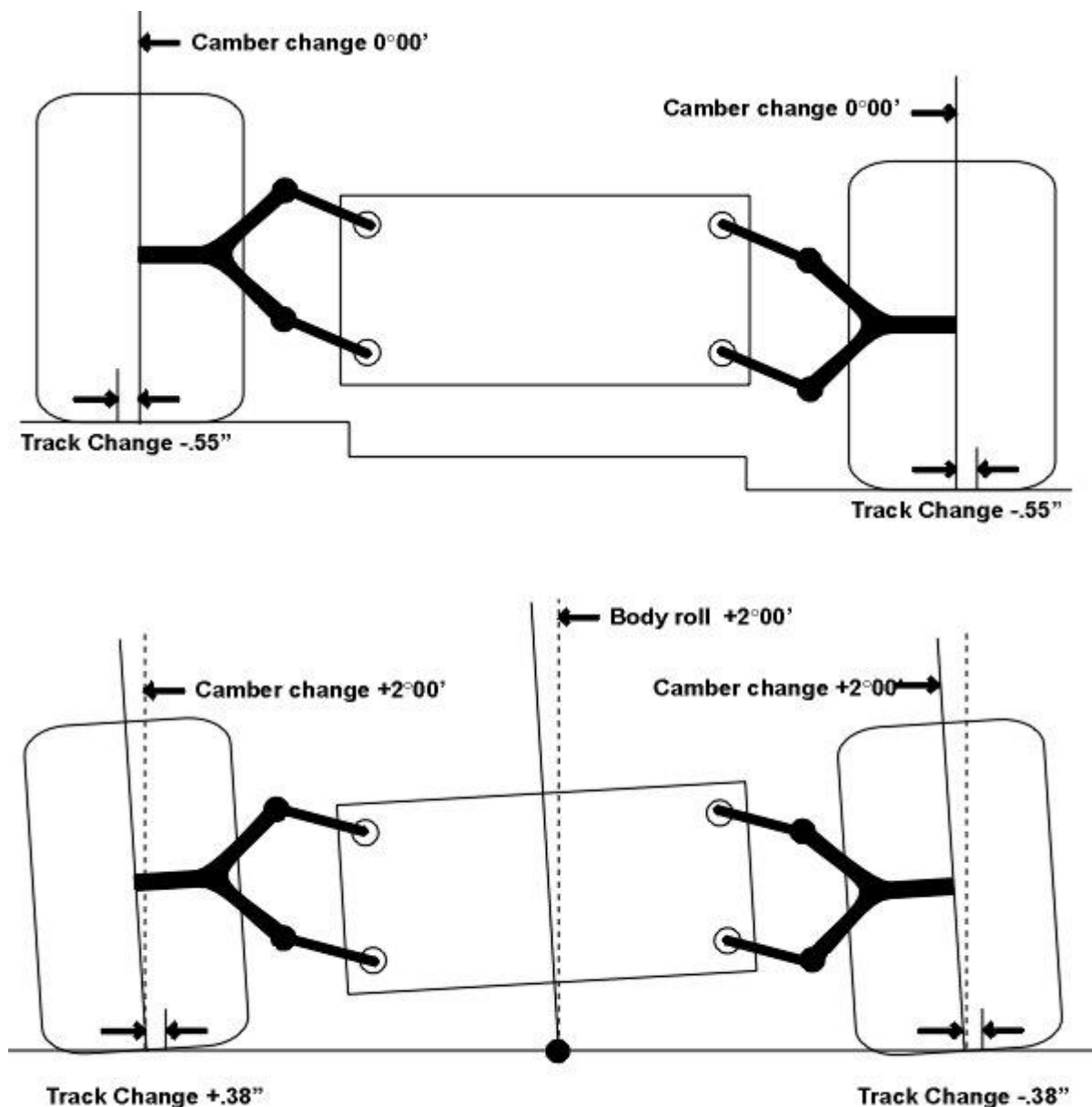
Low profile tyres are also fashionable in these days. Since the thickness becomes thinner, it is more resistant to side wall deflection under substantial cornering force. However, this is not much related to grip.

It must be mentioned that wide tyres are not always good. Especially are front tyres, the wider they are, the more resistance generates when they are steered. This create a heavy and insensitive steering feel, also more tyre roar and wear. If you want to modify your car by using wider tyres, always consider the drawback first. In my opinion, most well-sorted European cars have already equipped with the most suitable tyres.

2. Suspension Design

To maximize cornering grip, the suspension must keep the tyres perpendicular to ground under all conditions such as bump and body roll so that the contact patch area remains maximum.

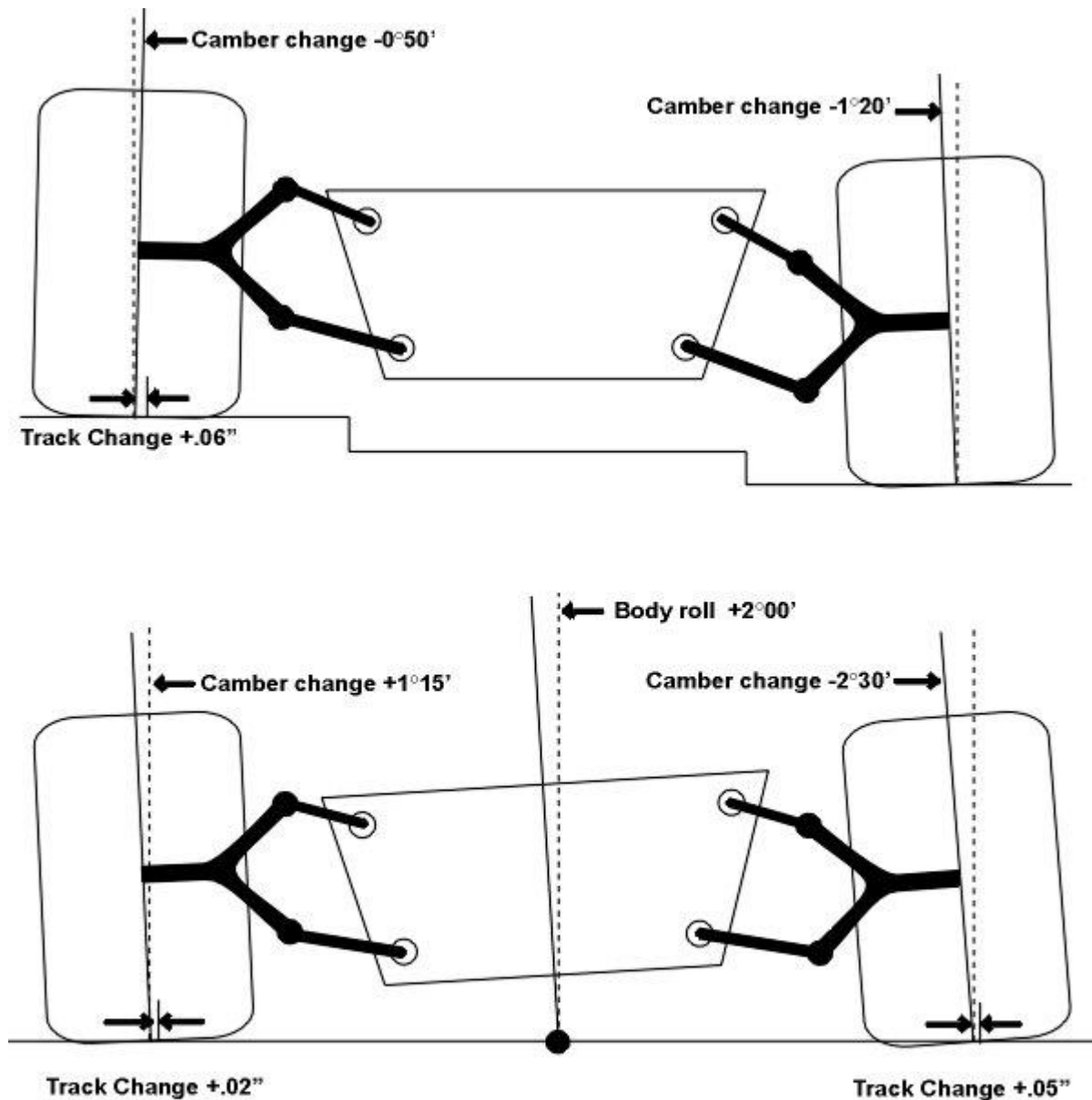
Generally speaking, double wishbones suspension does the best job to keep the tyre perpendicular to ground. The below figure shows how the conventional double wishbones suspension deals with bump and body roll. You can see there's no camber change at all under bump.



Equal length, parallel link double wishbones

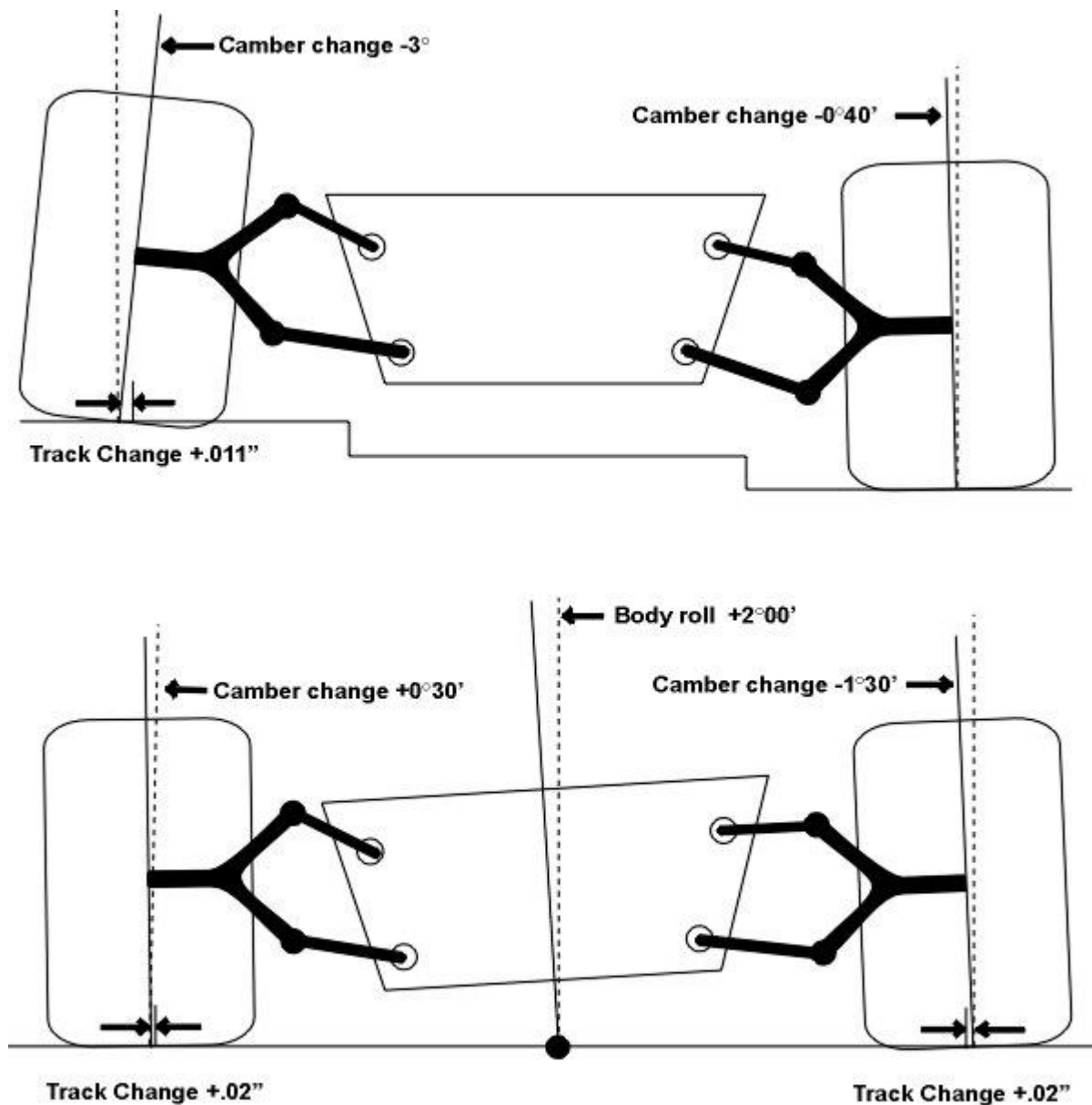
But the scene changes very much under body roll - camber changes for the same degree as the body roll. Track width also increases. Camber change reduces the contact patch area thus grip, and also introduces non-neutral steering (we'll discuss this later). Track width variation forces the tyres to slip thus also reduce grip.

Therefore engineers invented unequal length double wishbones. As shown in the below figure, the variation in camber and track width are largely reduced under body roll, although there is a small trade-off in wheel control under bump.



Unequal length, parallel link double wishbones

Unequal length non-parallel double wishbones (below) is even more impressive, whose camber angle at the heavy-loaded outside wheel is nearly unchanged, although it is less good under bump.



Unequal length, non-parallel link double wishbones

3. Weight Transfer due to lateral force

When a car is cornering at speed, the car's weight transfers from the inside wheel to the outside wheel. The rate of change is proportional to the height of center of gravity (CG), the lateral acceleration (in g) and inversely proportional to the track width. As this :

$$\text{Weight transfer} = (\text{Lateral acceleration} \times \text{Weight} \times \text{Height of CG}) / \text{Track width}$$

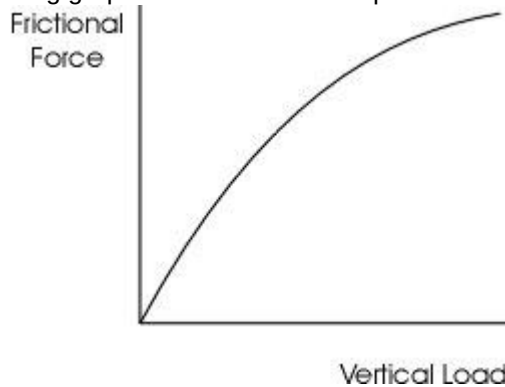
For example, a Porsche Boxster is cornering at 0.85 g. Assuming its track width is 1600 mm, height of CG is 500 mm and it weighs 1250 kg, then we can calculate the weight transfer is 332 kg. Assuming the car has a perfect 50 / 50 weight distribution between front and rear, then we can see each inside wheel takes 146.5 kg

while the outside 478.5 kg. What a big difference ! Therefore you can see the outside wheel has far more influence to handling than the inside wheel. This explain why we prefer unequal length non-parallel double wishbones, because it has the least camber change on the outside wheel.

If the car corners at extremely high g-force, our calculation may find the weight transfer approaching half the weight of the whole car, this means the outside wheels take all the load while the inside wheels are virtually unloaded ! Then the car is going to roll over ! Don't worry, this is almost impossible in reality, as it requires impractically high lateral acceleration. In our Boxster example, that equals to 1.6 g. Before that, the tyres would have already run out of its traction limit and slide.

However, if the car is the elk-frightening Mercedes A-class or Smart, with their exaggerate high center of gravity versus narrow track width, roll over might occurs even at a leisure cornering speed.

We've discussed the properties of weight transfer, but how does it relate to grip ?
Look at the following graph. It illustrates the Grip - Load characteristic of a typical tyre.



As you can see, as the load increases on the tyre, the grip generated by the tyre increases, but at a declining rate. This says, when weight transfer to the outside wheel, the grip on the outside wheel is increased, but not increase as much as the grip loss on the inside wheel.

Therefore the total grip decreases as weight transfer occurs. The more weight transfer, the less the total grip becomes.

Now can have some conclusions : to maximize the cornering grip, we must minimize the weight transfer. We can achieve this by lowering the CG, by reducing the weight of the car or by enlarging the track width. The first could be implemented by placing the heavy engine and transmission as low as possible, by using a wide V-angle or even boxer engine, and by lowering the seats. The second can be implemented by using lightweight materials and better chassis structure, and reducing the size of the car, but this seems to conflict with the third method. Therefore I don't recommend to increase the track width to as wide as Lamborghini Diablo. It won't help making the car nimble too. Another advantage of weight reduction is obvious: quicker to accelerate and to stop.

These are no secret. Any one interested in motor racing already knows them.

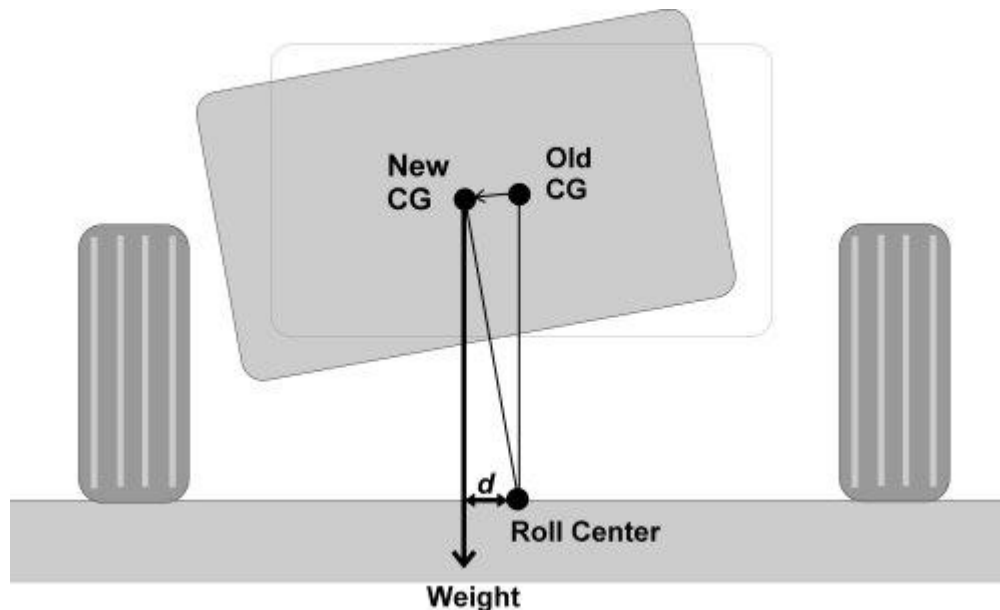
Weight versus Downforce

But then you may ask a question: reduce the car's weight also reduce the grip generated by the tyres, so what's the advantage ?

Firstly, because the car is lighter, centrifugal force acted on it is smaller. In theory the reduced grip could exactly withstand the reduced centrifugal force. Secondly, we could use aerodynamic downforce to increase the grip without increasing the centrifugal force. As a result, the car can corner faster.

4. Weight Transfer due to body roll

Body roll also introduces weight transfer thus reduction of total grip. Let's see the following drawing :



The lateral displacement of center of gravity (CG) is d . If we again use the Boxster example (track width 1600 mm, height of CG 500 mm, weight 1250 kg), if it rolls 10 degrees when cornering, d will be $500 \times \sin 10^\circ = 86.8$ mm. Then the load of the outside wheels can be calculated as: $(1250 \times (800 + 86.8)) / 1600 = 693$ kg while the inside wheels take 557 kg. So there is 68 kg weight transfer. Although it is not a great amount compare with the weight transfer due to lateral acceleration, its influence should not be ignored because camber change exists in this case.

We want to keep the body roll to an adequate level. We can use stiffer spring and anti-roll bar to reduce roll in the price of ride comfort. We can move the roll center, which is determined by the suspension geometry, as close to the CG as possible so that the roll moment is largely reduced, but this has a very bad drawback - a large jerking force will be generated and jerk up the body thus raise the CG. Alternatively, we could leave the body roll alone and try to lower the CG, so the weight transfer is also reduced.

After all, I don't recommend to eliminate body roll, since it is an important signal to tell us how well the car enters a corner and how close it approaches its limit. Body roll is a kind of feedback.

5. Four-Wheel Drive

Finally, 4WD can maximize the total grip of the car, both in straight line and cornering. The former case is easier to understand: compare with RWD and FWD cars, 4-wheel drive cars distributed less tractive force to each of its driving wheels, so it is less likely that the tractive force exceed the frictional force generated between tyres and ground. In other words, the driving wheels are less likely to slide. However, since we are talking about handling, straight line grip is not our interest.

For cornering grip, whose direction is perpendicular to the wheel's tractive force, the above mentioned theory is completely useless. The actual theory is quite complicated, it requires the concept of Slip Angle, which will be introduced in later sections. We will continue this discussion later.

Steering

Surprisingly, steering mechanism is not in our scope. In fact, most good cars today use rack-and-pinion steerings whose designs are more or less the same. What makes one car's steering superior to another is the weight distribution, drivetrain system and suspension geometry etc.

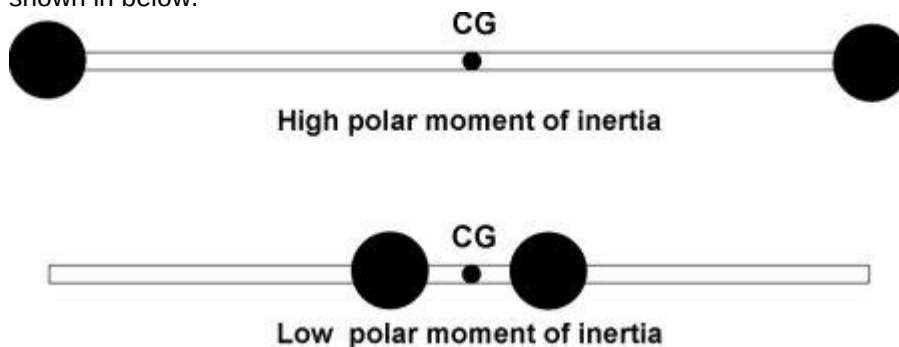
Steering Response

We always said mid-engined cars are superior in handling. Some ignorant auto journalists interpret as "because the heavy engine is placed in the middle of the car, it is easier to achieve 50 / 50 weight distribution between front and rear. In other words, the car is more balanced."

Wrong ! Most mid-engined sports cars have about 60% weight bias towards the rear, thanks to the engine, gearbox and differential are all located at the rear half of the car. In contrast, a well-sorted Porsche 924 has the engine in front and the transaxle at the rear, so it could actually achieve the perfect 50 / 50. Other good

front-engined cars such as BMW 3-series and Honda S2000 also achieve 50 / 50, thanks to the lay-back engines.

The reason we prefer mid-engined cars is, instead of better balance, mid-engined cars have superior steering response. This is because they have lower polar moment of inertia. Considering the two system shown in below.



Both of them have equal front to rear weight distribution. The one having the mass concentrating near the CG (in other words, lower polar moment of inertia) is easier to rotate about the CG. This could be easily verified by our experience. Applying the same steering force, the mid-engined car steers more quickly. The same for countering a steering action. This means it is responsive to steer and correct.

There is another advantage: since less effort is required to steer the car, we can reduce or even discard power steering, which always filter the feedback from the road thus downgrade the steering feel.

Dynamic Balance

Another reason we prefer mid-engined car is actually the slightly rear-biased weight distribution. In acceleration, we need more weight on the rear wheels to generate more traction for better launch. Obviously, FR cars are inferior in this respect. (FF cars, however, might be even better, but we shall see FF's disadvantages later)

If acceleration is not much related to handling, braking must be very decisive. When braking into a corner, weight transfers from the rear to the front, hence actually creating unbalance to a car which achieves 50 / 50 in static condition. In contrast, a 40 / 60 mid-engined car may achieve a real dynamic balance under braking.

Neutral / Understeer / Oversteer

We often hear these 3 terms in car magazines. I think few people would argue if I say they are the most important elements in the study of handling.

What is understeer ? Basically, if you turn the steering wheel and find the car steers less than you expect, the car is understeering. This is not because your subjective judgement goes wrong, in fact any car must have some degree of non-neutral steering due to the weight distribution, suspension design, tyre used, lateral acceleration and road conditions. Further more, a car could understeer in this corner and then oversteer in that corner. The whole picture is very complicated, so I'll spend more paragraphs to discuss this topic.

It seems that neutral steer must be more desirable than understeer and oversteer, but in fact it is not.

In fact, when running in straight line, we want a little bit understeer to make the car stable. When the car is subjected to side force, probably due to cross wind or the road's irregularities, understeer could resist the force and avoid the car to be steered automatically, therefore the driver need not to correct the steering frequently.

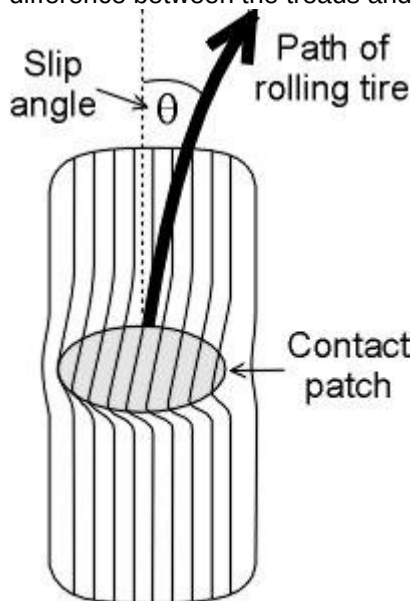
When the car is entering a corner, we also need a light understeer to provide the stability while the driver is easing off the brakes and building up cornering force. In mid corner, we need neutral steer. In the exit phase, a slight oversteer will be welcomed as it helps tightening the path. However, the degree of oversteer must be progressive and easily controllable by applying and easing throttle. We call this "Power Oversteer". Without power oversteer, we have to ease the throttle (thus loss time) or the car will run out of the corner.

However, I must make clear that what I say "slight understeer / oversteer" is usually deemed to be "near neutral steer" by most car magazines. This is because in reality there are too many cars running on severe understeer thus they used to them. In other words, if a car magazine said the Porsche 996 has mild understeer, it probably equals to "medium understeer" in our sense.

Basic Concept : Slip Angle

Before going on our study, we must understand the concept of slip angle first.

When a car enters a corner, all the tyres are turned with respect to the ground. Due to the elasticity of the pneumatic tyre, the tread in the contact patch will resist the turning action because there is friction generated between the rubber and the road surface. As a result, the treads on the contact patch will be distorted, whose direction always lags behind the direction of the wheel (See figure in below). We call the angular difference between the treads and the wheel's direction as Slip Angle.



Note : the car is turning left

In which direction the wheel is running ? It is the direction of the tread, not the direction of the wheel. I am not saying the tread has any ability to force the wheel to travel in its direction. On the contrary, the tread is only a sign showing how an arbitrary point on the tyre surface travels. If the arbitrary point travels in that direction, so does the wheel which is the summation of thousands of those points.

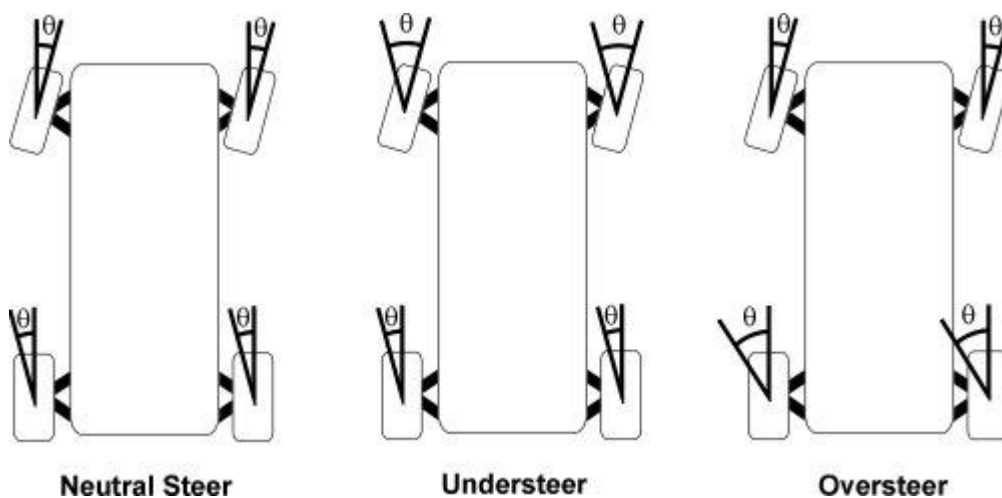
Now you must think the existence of slip angle must reduce the car's steering angle thus leads to understeer. In fact, it is not so if everything else are perfect. Because both the front and rear tyres have more or less the same slip angles, they counter each other thus the resulting steering angle remains unaltered.

However, if the front and rear wheels have different slip angles, then we get understeer and oversteer :

Understeer : Front Slip Angle > Rear Slip Angle

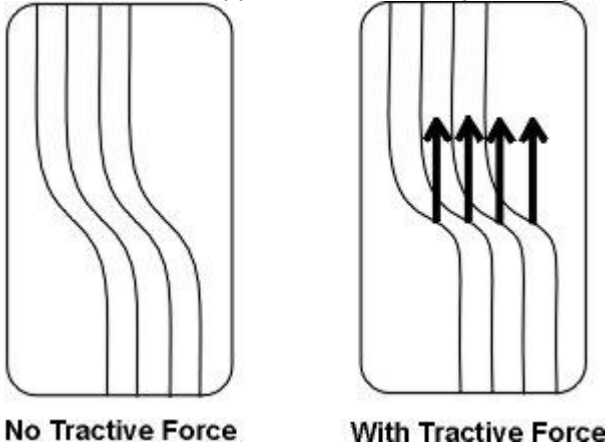
Oversteer : Front Slip Angle < Rear Slip Angle

Neutral steer : Front Slip Angle = Rear Slip Angle



Non-neutral steer due to Tractive Force

Car magazines often prefer the handling of rear-wheel-drive cars. They say FWD cars usually understeer while RWD is easier to provide power oversteer. Now, we use the concept of Slip Angle to explain this. Consider a driving wheel, which is under cornering and has created slip angle. If tractive force (that is, the pulling force from the engine) is applied, the slip angle will increase (See Figure in below). This is because the tractive force applied between the tyre and ground will distort the tread on the contact patch further.



No Tractive Force

Now the scene is clear.

With Tractive Force

FWD cars has the front wheel's slip angle > rear wheel's. This result in **Understeer**.

RWD cars has the front wheel's slip angle < rear wheel's. This result in **Oversteer**.

4WD cars, if the front / rear torque split is equal, has equal F/R slip angles, thus result in

Neutral steer.

(Remind you, understeer, oversteer and neutral also depend on suspension design, weight distribution etc. So we cannot say all FWD cars must understeer or all RWD car must oversteer. In fact, car makers usually design the suspension geometry to compensate the non-neutral steering generated by FWD / RWD and weight distribution.)

Power Oversteer and Lift-off Oversteer

The more tractive force we apply, the larger slip angle is created in the driving wheel. Therefore, for the RWD cars, we can use the throttle to control the degree of oversteer. When the car is entering a corner too fast and seems likely to run wide, we can correct its direction by increasing the throttle (not to do this before reaching the mid corner !), then the car oversteers. If we find the correction is too much, we can ease the throttle and let the car returns to neutral steer or even mild understeer, depends on the suspension design and weight distribution.

Only RWD cars or rear-biased 4WD cars can do this ! In the same situation, the driver in a FWD car has nothing to do other than easing the throttle, slow down the car thus reduce the centrifugal force, and hope the car can overcome the corner. There are many disadvantages :

1. You lose time during slow down.
2. You lose engine rev during slow down, thus the engine takes longer to rise back to the useful power band once you exit the corner.
3. Very often, if you miscalculate, you are unlikely to have sufficient road ahead for you to slow down, especially in tight corner.

Therefore we always say RWD car is superior than FWD car in handling. There are, however, some well-sorted front-driver (especially some GTi) can play "lift-off oversteer", which is actually the reverse of "power oversteer" - a degree of permanent oversteer is built into the car but is only accessible when the car is pushing to the limit and with throttle disengaged. Step down the throttle again will reduce the oversteer and even back to understeer. Anyway, obviously this is still not as controllable as "power oversteer". While power

oversteer can extract a lot of oversteer - actually depends on throttle - lift-off oversteer is rather limited, simply because it is impossible to build a lot of permanent oversteer to the chassis without deteriorating handling in lower speed or straight line.

Once again I have to emphasize that the power oversteer must be highly controllable by the driver, otherwise the car may lose control and spin. To make a good power oversteer car, the secret is to match the power and cornering limit perfectly at the speed concerned. If the cornering limit exceeded the power, the rear wheels will grip hard and refuse to slip. In contrast, if the cornering limit is too low or the engine torque is too high at the speed concerned, the rear end will slide severely once the throttle is pressed. Therefore, the cornering limit must be set at a level where the engine output, at the speed and road we normally want the car to power oversteer, has just sufficient power to exceed. To implement it, choose a suitable set of tyres, applying suitable amount of downforce and an adequate front / rear weight distribution is very crucial.

RWD versus 4WD

Basically, 4WD does not introduce power oversteer. However, most people still prefer it simply because it provides superior cornering grip thus improve cornering speed. As I have promised earlier in the Cornering Grip section, here I'll explain how 4WD improve cornering grip :

Consider a driving wheel running in a corner. Due to the frictional force applied from the road surface, the tread in the contact patch distorts and creates slip angle. The faster the car corner, the more centrifugal force generates thus the larger the slip angle becomes. You can interpret this as the elastic distortion of the tyre generates a counter force to keep the car fighting with the centrifugal force. When the car is accelerated fast to the extent that the elasticity of the tyre reaches its limit, it could not distort anymore, thus more speed will lead to the tyre slide, and the car lose grip. This point is what we call "Cornering Limit".

A FWD or RWD car has already a lot of tyre distortion (slip angle) in the driving wheel because the tractive force is shared by only two wheels. Therefore there is not too much space left before the tyres running into their cornering limits. On the contrary, 4WD cars distribute tractive force to all wheels, thus each wheel shares considerably less tractive force thus create smaller slip angle in cornering. The car can corner at higher speed before the slip angle reach the cornering limit.

Grip aside, we concentrate back to our current topic - steering tendency.

There is always argument that whether the neutral steer of 4WD is better than RWD's oversteer. Although neutral is more favourable in the entry phase and mid corner phase during cornering, it doesn't provide the "correctability" of power oversteer in the exit phase. Remember, no driver could avoid miscalculation, no matter Mrs. Robinson or Michael Schumacher. Normally we need to feel the car's attitude and the road condition every moment before deciding how to control the car in the next moment. In this sense, RWD's controllable power oversteer is what we want.

Moreover, power oversteer of RWD ask the driver to intervene the throttle during cornering. This let him feel more involving and that he is mastering the car. In contrast, 4WD cars let the tremendous grip, the limited-slip differential and even the computer to rule the car's cornering. Therefore we always hear road testers said RWD is more fun to drive.

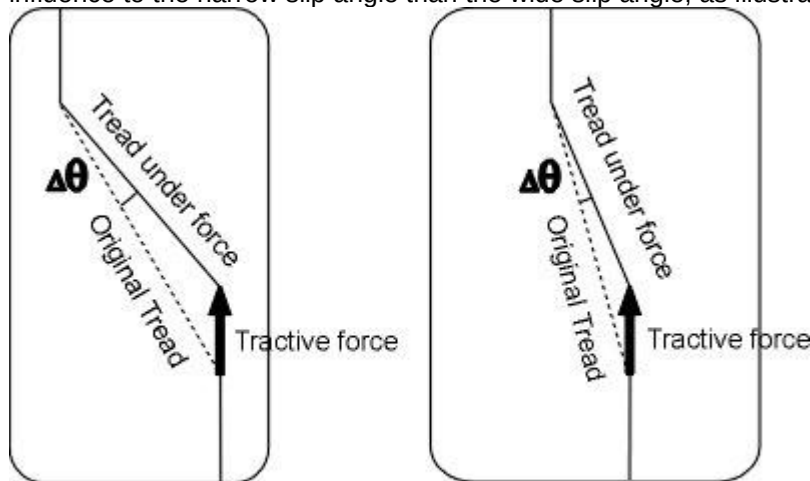
I am not saying 4WD cannot have power oversteer. Bugatti EB110, with its 30/70 front-to-rear torque split, did that beautifully while providing tremendous grip. Even though a 50/50 4WD car like Mitsubishi Lancer Evo V could achieve slightly power oversteer by means of well-sorted suspension geometry. For example, if the suspension is setup such that to introduce rear outside wheel positively cambers when subjective to body roll, the contact patch area decreases thus slip angle increases, then power oversteer is also available. However, you cannot set the suspension to provide power oversteer as much as RWD car since there is a trade-off in total grip and straight line stability.

New Trend for RWD cars

In the past 2 decades, we saw car makers gradually increases understeer in RWD cars, making them more "secure" to drive. Porsche 996 is a good example. Its predecessor 911 used to offer hell a lot of oversteer, now the 996 becomes a very civilised GT.

This is partly due to the market orientation (it seems the wealthy customers tend to love secure rather than excitement), partly due to the use of wider tyres. In the past 2 decades, tyres of sports cars had been widened for about 50%, in addition to the growth in diameter, the contact patch area had been largely increased. Of course this is intended to increase the grip. However, increased contact patch area means every square inches of the contact patch carries less cornering force, so the tread distort less and the slip angle is reduced.

It is known that for the range of slip angle we concern (normally less than 20°), tractive force has less influence to the narrow slip angle than the wide slip angle, as illustrated in below :



Narrow Tire

Wide Tire

Therefore, when apply the same power, the rear wheel slip angle increases in a lesser rate in wider tyres. In other words, power oversteer is less obvious.

This explain why the 115 hp version BMW Z3 1.9 has virtually no power oversteer ability. Its engine lacks the power to generate sufficient slip angle to the wide 205 rear tyres.

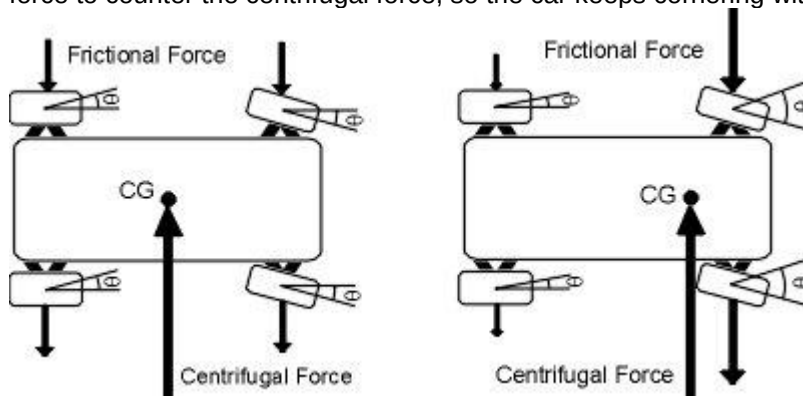
If it get considerable more power, like the M Roadster, power oversteer would have come back. But then again the car maker is very likely to install even wider rear tyres in order to cope with the increased performance, as did in the M Roadster. So once again the power oversteer is quite limited.

In my opinion, this trend is quite frustrating to the front-engined RWD cars. It makes them having less and less fun to drive, although the increased grip will ultimately improve cornering time. To mid-engined cars, whose rearward weight bias used to create some undesirable oversteer, the adoption of wider tyres could actually improve the handling and driving fun.

Non-neutral steer due to front / rear weight distribution

Here we are going to discuss the theory behind front-heavy cars tend to understeer and rear-heavy cars tend to oversteer.

When a car is cornering, its CG is subjected to centrifugal force. The tyres generate slip angle thus frictional force to counter the centrifugal force, so the car keeps cornering without slide. (See figure in below)



If the car is heavier at the front, that is, the CG is near the front, obviously the front tyres shares most of the centrifugal force thus they have to generate larger slip angle thus larger frictional force to counter the centrifugal force. As a result, the front slip angles exceed the rear's, and understeer occurs.

On the contrary, rear-heavy car has larger slip angle at the rear, thus introduce oversteer. Similarly, we can find a 50/50 balanced car having neutral steer. This is our choice for optimum handling. We don't really need oversteer in this case, because such oversteer is not controllable, unlike power oversteer which we have found in RWD cars.

The result favours front-engined, RWD cars (FR), which is easiest to achieve 50/50 F/R weight distribution.

Mid-engined, RWD cars (MR), with its slight rearward weight bias at about 40/60, is slightly inferior in here. But remember, its superior steering response, steering feel and dynamic balance are probably more than enough to compensate.

Front-engined, FWD cars (FF) is the worst in here, and far worst. As all the heavy mechanical parts - engine, transmission, differential - hang over the front end, the front axle normally takes up to two-third of the weight. This tends to create heavy understeer. In addition to the understeer generated by the FWD configuration, the result is even worse. This requires a lot of work to do in the suspension geometry and steering mechanism for compensation. And there must be some trade-off. Take an Alfa GTV as an example. It has to install an ultra-quick 2.2 turns steering to counter understeer, thus requires quite a lot steering effort. If power steering were increased, steering feel must be deteriorated. The multi-link rear suspension was also probably chosen for compensating the understeer because the geometry is more tunable than the original MacPherson strut.

There is another problem troubling the Alfa - the 3.0 V6 version, which is intended to be the range-topper, found its even heavier front end leads to inferior handling than the cheaper and slower 2.0 version. This is a headache to the marketing personnel.

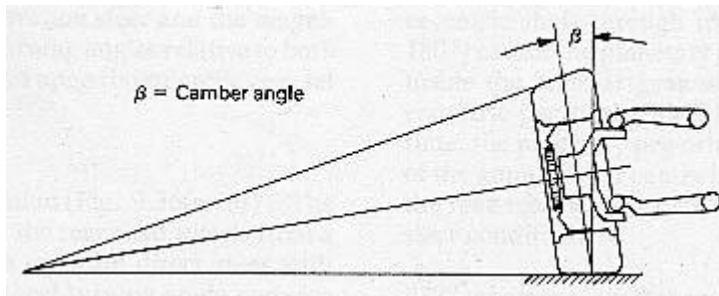
However, once again I have to point out that everything must have exception, especially when all mass production cars are also limited by other factors such as packaging, requirements for refinement and cost etc. When both under these limitations, a well-sorted Alfa 156 could outhandle an ill-fated BMW 3-series. Although recently RWD luxurious / sports sedan / compact elegant sedan seems to be reviving, FF is still the main trend for the majority budget cars due to its lower cost and space-saving advantage.

Non-neutral steer due to Suspension Geometry

We've said a lot suspension geometry can alter the steering, and it is usually used to compensate the undesirable steering tendency due to uneven weight distribution and FWD / RWD. Now I'll briefly go through this.

Camber - Decisive to understeer and oversteer

As shown in below, if a wheel is not perpendicular to the road, then it is **cambered**. If it leans towards to the center of the car, then it is **negative cambered**. (or "toe-in"). If it leans outwards to the car, it is **positive cambered** (or "toe-out", as shown in the following picture.)



When a wheel has positive cambered, due to the elasticity of tyres, the wheel will be reshaped to something like the base of a cone. It will have a tendency to rotate about the peak of the cone, as shown in the picture. Now, you will see the wheel tries to steer away from the center of the car.

If both the right and left wheels are positive cambered (that means they lean to opposite direction), the steering tendency will be cancelled so that the car remains running in straight line. If the car is turning into a corner, weight transfer put more load on the outside wheels than the inside wheels, that means the outside wheel's steering tendency will have more influence to the car. As the positive-cambered outside wheel tries to steer the car to the outside of the corner, the car will be understeered.

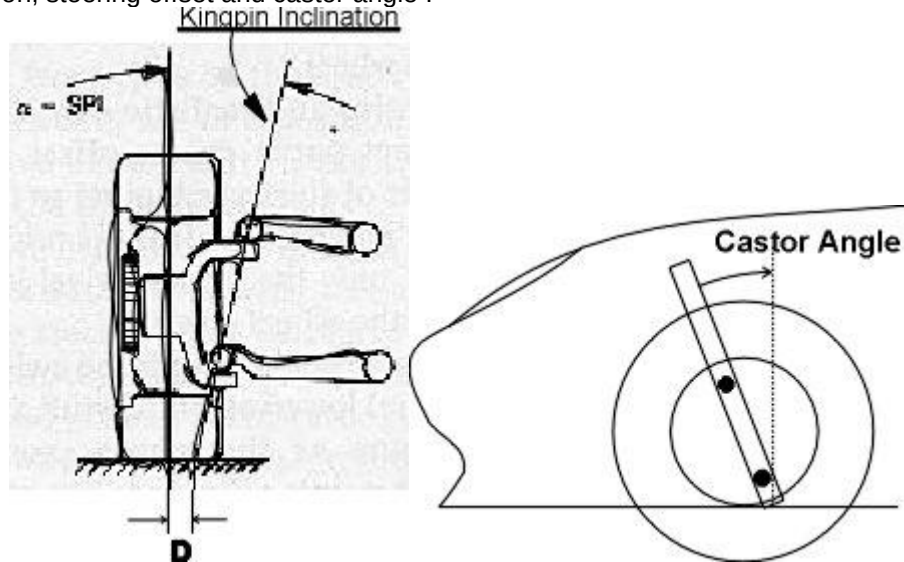
On the contrary, if both wheels are negative cambered, the car will oversteer.

For FF cars, we could introduce some negative camber to the front wheels to reduce the understeer. Similarly, more positive camber could be employed to the rear-heavy 911.

We may deliberately need positive / negative camber, but we don't want the camber to be changed when the wheel meets bump or when the car body rolls into a corner, otherwise the handling will be very unpredictable or even uncontrollable. Therefore we prefer a suspension geometry whose camber varies little under all conditions. As said many times in before, double wishbones, especially is non-equal length, non-parallel double wishbones, is generally regarded to do the job best. Therefore from sports car to Formula One, all the high performance cars use it. For other kinds of suspensions.

Steering Feedback and Torque Steer

The steering must offer enough "feel" to the driver so that he can sense what's happening as he approaches the cornering limit of the tyres. It must also have some self-returning action, but it cannot be so heavy as to cause fatigue or loss of sensitivity. This feel, feedback and self-returning action is a function of kingpin inclination, steering offset and castor angle :



The more the steering offset D, the more self-returning effort generated. Similarly, the larger the castor angle, the more self returning action.

If the car is FWD, the steering offset D will introduce torque steer. This is because the tractive force will try to pull the center of contact patch of the front wheels forward, thus the wheel will rotate about the point the kingpin axle projected to the ground. The torque steer moment is the product of D and the tractive force. Therefore the amount of torque steer is proportional to D. The solution is to build more inclination to the kingpin so to reduce D. This is easy to be implemented in double wishbones suspension which is shown in the picture, but not MacPherson strut, whose kingpin also serves as spring and shock absorber. If we incline the kingpin too much, there will be too much lateral force transmit via the spring / shock absorber to the car body, thus causing shake and instability.

Therefore we say MacPherson strut is not very suitable for FWD cars having a powerful engine. Alfa Romeo 164 is one of the examples, whose torque steer ruined the otherwise brilliant handling. No wonder its successor, 166, has switched to double wishbones front suspensions.

Chassis Rigidity

The last method to improve handling is to strengthen the chassis. Since the late 80s, we saw chassis rigidity of new cars have increased a lot. Whenever a new car is launched, the manufacturer must claim its torsional rigidity has been increased by at least 20%. This is partly due to the requirements for crash protection, partly in order to improve handling.

Consider a car with a very weak chassis which is easy to flex and twist under force. If it employ stiff springs and dampers to the suspension, the shock cause by road irregularity will be transferred to the chassis directly. The weak chassis will be twisted and bent, thus the suspension geometry will be reshaped, creating non-neutral steer and other side effects that is not the original suspension design intended to cope with. Therefore a weak chassis must ride on softer spring and dampers.

For the benefit of handling, we always want stiff spring and damper as long as ride comfort is acceptable. So we need a rigid chassis which could cope with the stiff suspensions without flex or twist.

Suspension Geometry, Types, Ride and Handling

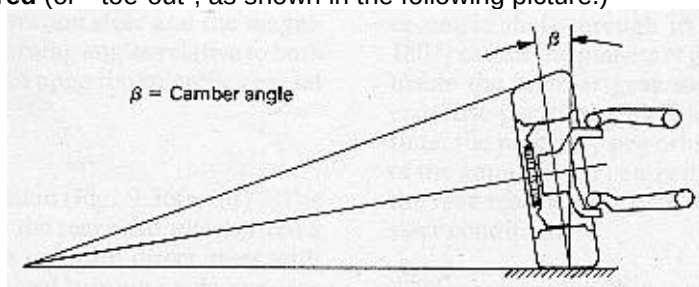
Basically, suspensions are employed to deal with hump in road surface, in other words, enhancing ride comfort. When a car rides over a hump, the springs are compressed, store the energy thus provide shock absorption. The energy will be released quickly when the springs bounce back. Dampers are employed to smooth and slow down the bounce motion, this is called "Damping". Without dampers, the car will bounce up and down severely and quickly, this is perceived as uncomfortable. Study found that ride is perceived as comfortable by human when the bouncing frequency is 1 to 1.5 Hz. If it exceeds 2 Hz, most people feel the ride harsh. Therefore ride quality is mostly controlled by the selection of suitable springs and dampers.

In order to achieve ride comfort, we create suspensions and let the wheels movable with respect to the car body. Inevitably, this creates many many problems in handling. When the car is turning quickly into a bend, centrifugal force will roll the car body. Body roll leads to the weight transfer towards the outside wheels, it also changes the suspensions geometry which changes the camber angles of wheels. Change of camber accompanies with weight transfer result in unwanted understeering or oversteering. If brakes are applied in the bend, castor angles will also be changed, that may further deteriorate understeering / oversteering or even introduce torque steer. (Don't understand ? No problem, you will have a clearer view in the following paragraphs)

Camber - Decisive to understeering and oversteering

This is a very important concept. We must learn this before going on our study.

As shown in below, if a wheel is not perpendicular to the road, then it is **cambered**. If it leans towards the center of the car, then it is **negative cambered**. (or "toe-in"). If it leans outwards to the car, it is **positive cambered** (or "toe-out", as shown in the following picture.)



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If both the right and left wheels are positive cambered (that means they lean towards opposite directions), the steering tendency will be cancelled so that the car remains running in straight line. If the car is turning into a corner, body roll puts more weight on the outside wheels than the inside wheels, that means the outside wheel's steering tendency will have more influence to the car. As the positive-cambered outside wheel tries to steer the car to the outside of the corner, the car will be understeered.

On the contrary, if both wheels are negative cambered, the car will oversteer.

A Good Suspension must :

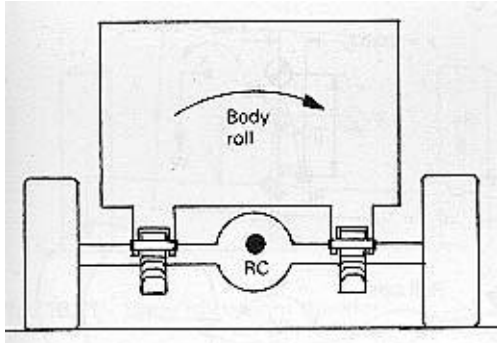
- 1) Provide independent shock absorption to individual wheels. That means, when one wheel rides over a hump, the shock will not be transferred to other wheels.
- 2) Has adequate body roll. Excessive body roll leads to too much weight transfer thus influence the steering response. It is not comfortable too. Restrict body roll to minimal may create uncomfortable feeling because of excessive g-force. Moreover, body roll could provide information to the driver, telling him the state of cornering and whether the car has reached its limit. Completely eliminate body roll is not at all good.
- 3) Has a good geometry such that wheel cambers remain unchanged in all conditions, that is, acceleration, braking, cornering, load and bumps.

Body roll suppression usually conflict with ride comfort, because the former requires stiffer spring and dampers while the latter vice versa. Nevertheless, clever suspension geometry may improve body roll

without altering the ride. Here in below we are going to discuss the most popular kinds of suspension geometry.

Non-independent suspension

Live / Dead axle



Until the late 70s, most cars still used this simple non-independent suspensions, especially at the rear axle. Basically, it is a rigid axle fixed between left and right wheels. The car body is suspended by leaf springs or coil springs on the axle / wheels unit.

As you can see, the wheels are not independent. When one wheel rides on a hump, the shock will be transferred to another wheel. Besides, both wheels will be cambered, thus non-neutral steering is inevitable. If the axle is also the driving axle, it is called **Live Axle**. Live axle is very heavy. It consists of the final drive / differential, drive shafts and a strong tube enclosing all these things. Since the whole axle is rigidly fixed to the wheels instead of suspended by springs, the so-called **Unsprung Weight** is very high.

What is the result of high unsprung weight ? Assuming a live axle meets a hump and "jump" quickly upward, the more weight it has, the more momentum it gains (because momentum = the product of mass and velocity). That means the more momentum the springs have to deal with. Of course, springs cannot absorb all the momentum, so eventually part of the latter will be transferred to the car body in the form of shock. Therefore live axle is never good at ride quality.

If the axle is not the driving axle, it is called **Dead Axle**. Without the driving mechanism incorporated, dead axle has much less unsprung weight, so its ride quality is better than Live Axle. Anyway, comparing them is useless - it does not make sense for a car to use dead axle in the non-drive wheels while using a suspension advancer than live axle in the driving wheels. Independent MacPherson suspension is rather easy and cost-effectively to replace the non-drive dead axle. If a car maker cannot afford such little additional cost, it must not willing to employ advancer suspensions in the driving wheels also.

Live / Dead Axle have another disadvantage - body roll is not sufficiently suppressed. Springs are the only element which control the body roll, however, stiffen the springs will inevitably deteriorate ride quality. Moreover, if coil springs are used, lateral force due to cornering will lead to transverse movement of the car body, thus result in weight transfer and affect steering response.

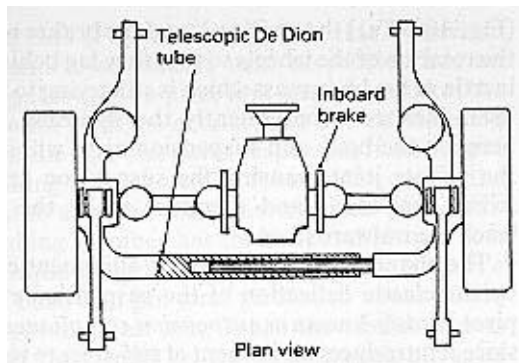
The popular solution was to add some control arms between the car body and the axle, such as Panhard rod and Watt link. However, they are out of our scope.

Advantage: Cheap. Body roll does not influence the camber of wheels.

Disadvantage: Non-independent, bad ride quality, both wheels cambered on bump.

Who use it ? Some American sedans, Ford Mustang, Falcon, most SUV.

DeDion Axle



Although independent suspensions were invented decades ago, non-independent suspensions still dominated the market until the late 70s. The first reason was: cheap. The second reason: it offers quite good handling despite of poor ride. Since the wheels are rigidly linked by an axle, they remain perpendicular to the road surface regardless of body roll. Therefore the car corners quite stable. In contrast, in many types of independent suspensions, camber angle may be changed due to body roll.

However, as explained before, live axle has too much unsprung weight, thus leads to poor ride quality. Therefore many budget sports cars or coupes chose DeDion Axle (rear) suspensions over live axle.

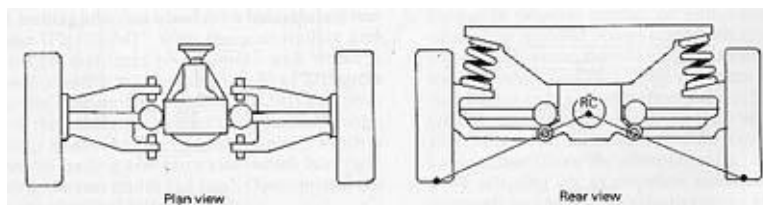
DeDion axle suspension has much less unsprung weight because the final drive / differential and driving shafts are not rigidly attached to the wheels. Like independent suspensions, they are part of the car body and flexibly linked to the wheels by universal joints. In other words, they are sprung.

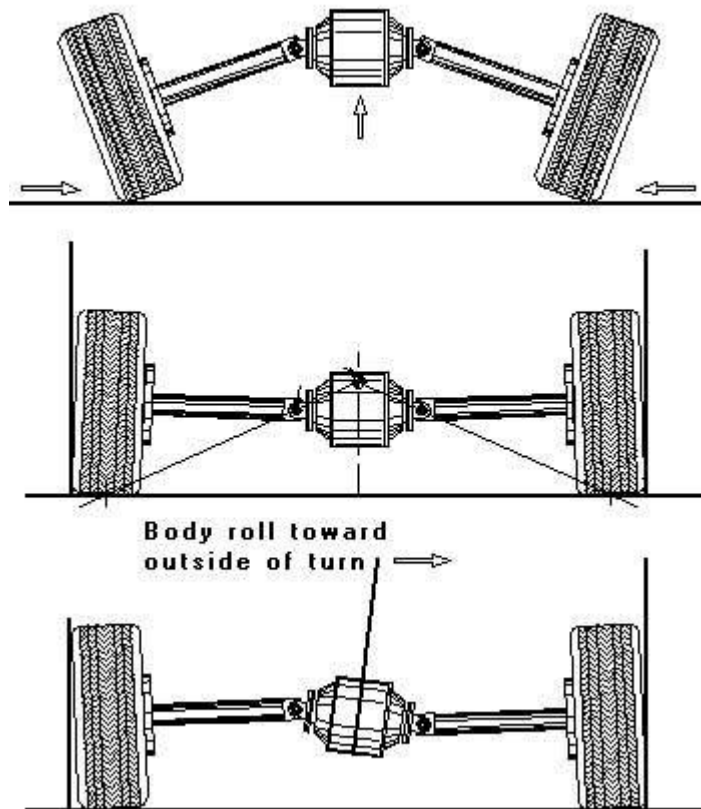
The wheels are interconnected by a DeDion Tube, which has a sliding joint to permit wheel track variation during suspension movement, this help refining ride quality too. The DeDion tube keeps both wheels parallel to each other under all conditions, so they are always perpendicular to the road surface regardless of body roll.

Advantage:	Still cheaper than most independent suspensions. Body roll does not influence the camber of wheels. Better ride quality than Live Axle.
Disadvantage:	Non-independent, ride is still worse than independent suspensions. Both wheels cambered on bump.
Who use it ?	Caterham, Vector, Smart.

Independent Suspensions

Swing axle suspension





This is a very old independent suspension, used by some sports cars since the 50s, such as VW Beetle, Porsche 356 (which was based on Beetle) and Mercedes' famous 300SL Gullwing (1954). However, it disappeared for at least 2 decades because it has so much weakness. The only advantage is - it provides independent shock absorption.

Handling is really awful, as camber angle can be noticeably changed by bouncing motion (as shown in the first picture), change of static weight of the car (second picture) and body roll (third picture). Especially is the body roll, which makes both wheels lean towards the corner, thus result in severe oversteer. This explain why the Mercedes 300SL Gullwing was criticised as very unpredictable and difficult to handle.

Camber variation can be reduced via using longer swing arms, but this could create problems in packaging. It engages the space for rear seats and even the boot.

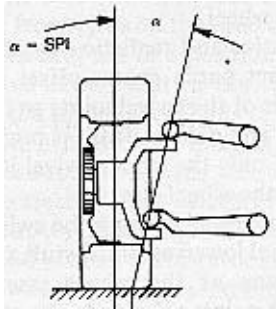
Another solution is to introduce inherent understeer by setting the wheels negative cambered. This could compensate the oversteer during cornering but the drawback is the instability in straight line. To cars as slow as VW Beetle, swing axle shows its advantage in ride comfort over contemporary non-independent suspensions while the weakness in handling is not easily seen. For Porsche 356, at least in the less-powerful early versions, the problem is not severe, too. In later years, when the car got bigger and bigger engine, Porsche realised that the days for swing axle had nearly finished. That came true when the 911 launched in 1963, used trailing arm at the rear instead of swing axle.

Advantage: Independent ride.

Disadvantage: Very bad handling.

Who use it ? Mercedes 300SL (1954), VW Beetle, Porsche 356 etc.

Double wishbones suspension



To many suspension designers, double wishbones (or "A-arms") is the most ideal suspension. It can be used in front and rear wheels, it is independent and most important, it has near perfect camber control. For 40 years and even today, this is the first choice for racing cars, sports cars and demanding sedans.

Basically, double wishbones suspension always maintains the wheel perpendicular to the road surface, irrespective of the wheel's movement. This ensure good handling.

Traditional double wishbones consists of 2 parallel wishbone arms of equal length, which has the drawback of excessive tire scrubbing because of the large variation in track width as the wheel moved off the neutral position. Therefore engineers developed **unequal-length** non-parallel A-arms to solve this. By tilting the upper A-arm, anti-dive function is also achieved.



<< Porsche 993's rear suspension

Double wishbones suspension has been very popular in American cars. Not so in Europe because cars in there are smaller thus cannot accommodate this relatively space-engaging suspension. Besides, it is more costly than MacPherson strut and torsion beam because it involves more components and more suspension pick up points in the car body. Owing to these reasons, very few small cars adopt it. One of the few examples is Honda Civic.

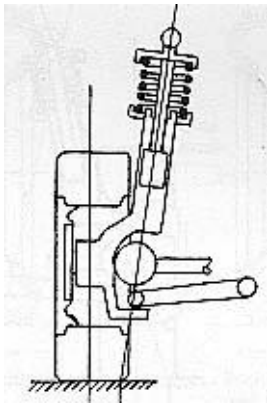
This does not mean American cars have better handling. No, due to their larger size and weight and the less effort spent in suspension tuning, the majority of double wishbones-equipped American cars actually handles worse.

Advantage: Ideal camber control leads to good handling.

Disadvantage: Space engaging and costly.

Who use it ? American sports cars and some sedans, most European pure sports cars like Ferrari, TVR, Lotus some European sedans, most Honda many many many.

MacPherson strut suspension



The MacPherson strut suspension was invented in the 1940s by Earl S. MacPherson of Ford. It was introduced on the 1950 English Ford and has since become one of the dominating suspensions systems of the world because of its compactness and low cost.

Unlike other suspension designs, in MacPherson strut suspension, the telescopic shock absorber also serves as a link to control the position of the wheel. Therefore it saves the upper control arm. Besides, since the strut is vertically positioned, the whole suspension is very compact. To front-wheel drive cars, whose engine and transmission are all located inside the front compartment, they need front suspensions which engage very little width of the car. Undoubtedly, MacPherson strut suspension is the most suitable one.

Nevertheless, this simple design does not offer very good handling. Body roll and wheel's movement lead to variation in camber, although not as severe as swing axle suspension. From a designer's viewpoint, its relatively high overall height requires a higher hood and fender line, which is not very desirable to sports cars' styling.



<< Hyundai Atoz's MacPherson strut

Like double wishbones suspension, MacPherson strut can be adopted in both front and rear wheels. In the 80s, there are many budget sedans employed Mac strut in all corners, the most famous is Fiat's Type 4 and Tipo platforms, on which Fiat Croma, Lancia Thema, Saab 9000, Fiat Tipo, Tempra, Lancia Delta, Dedra etc. were based. None of them was famous of handling. Basically, Alfa Romeo's GTV / Spider is also based on the Tipo platform, however, after experienced unsatisfactory handling during testing, the rear MacPherson struts were replaced by the pricier multi-link suspensions.

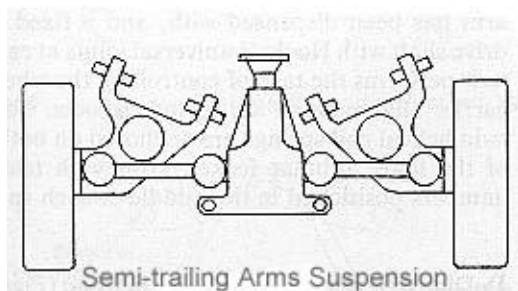
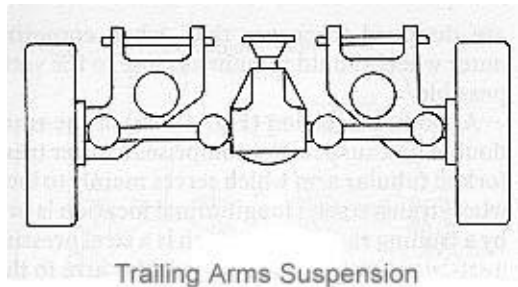
Advantage: Compact and cheap.

Disadvantage: Average handling.

Who use it ? Most front-wheel drive compact cars.

Independent Suspension

Trailing arm and Semi-trailing arm suspension



Compare with the following rear suspensions, Trailing arm / Semi-trailing arm suspensions are rather old. It was commonly used in nearly all mid-price to high-price sedans before multi-link rear suspension became popular in 1990s. From '82 BMW 3-series to Mercedes 560SEC, even the Porsche 911, trailing arm / semi-trailing arm suspensions dominated half the world.

Trailing arm suspension (the upper picture) employs two trailing arms which are pivoted to the car body at the arm's front edge. The arm is relatively large compare with other suspensions' control arms because it is in single piece and the upper surface supports the coil spring. It is rigidly fixed to the wheel at the other end.

Note that it only allows the wheel to move up and down to deal with bump. Any lateral movement and camber change (with respect to the car body) is not allowed. Nevertheless, when the car rolls into a corner, the trailing arm rolls for the same degree as the car body, thus changes camber angle (with respect to the road surface). Now, you can see both wheels lean towards the outside of the corner, thus lead to understeer. Because of this reason, pure trailing arm was forgotten by car makers long long ago. Instead of it, they adopted semi-trailing arm.

Semi-trailing arm suspension (the lower picture) has the trailing arm pivoted at inclined angles - about 50 to 70 degrees. Otherwise are the same as trailing arm suspension. Apparently, the semi-trailing arms are half trailing and half transverse. You can analyse it by splitting it into two vectors, one is the trailing component and another is the transverse component. The trailing component leads to understeer, as already mentioned. On the other hand, the transverse component is actually equals to a swing axle suspension. Now, you may remember that the swing axle suspension always introduce oversteer due to body roll. As a result, the two components cancel each other and result in near neutral steering response.

Semi-trailing has a disadvantage - when the wheel moves up and down, camber angle changes, unlike double wishbones suspension.

No matter semi-trailing arm or pure trailing arm suspensions, since they are rigidly attached to the wheels, inevitably more shock and noise could be transferred to the car body, especially under hard cornering or running on bumpy roads. Moreover, a lot of unsprung weight of the trailing arm leads to poorer ride quality. Therefore most modern sedans replace it with multi-link or double wishbones suspension. Trailing arm / Semi-trailing is disappearing in the industry.

Advantage: All round, few weakness.

Disadvantage: Less refined than multi-link.

Who use it ? Many sedans and coupes.

Torsion beam suspension



Most modern mini cars up to C-segment (for instance, VW Golf) employ torsion beam as the rear suspension. Why? compare with double wishbones, multi-link and trailing arm suspensions, it engages little width of the car, thus enable greater rear seat room. It is cheaper too. Compare with MacPherson strut, its shock absorber is shorter and can be inclined steeply away from the vertical, thus engage less boot space.

In fact, torsion beam suspension is only half-independent - there is a torsion beam connecting both wheels together, which allows limited degree of freedom when forced. For some less demanding compact cars, this save the anti-roll bars. On the contrary, it doesn't provide the same level of ride and handling as double wishbones or multi-link suspensions, although in reality it is superior to its only direct competitor, MacPherson strut. Most of the Europe's best handling GTIs employed this suspension.



Golf's torsion beam rear suspension



Fiat Punto's torion beam

Advantage: Compact, cheap.

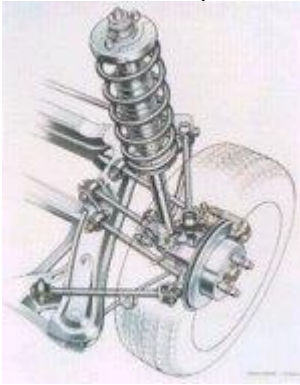
Disadvantage: Theoretically inferior ride and handling.

Who use it ? Most European mini cars up to Golf-class.

Multi-link suspension

Since the late 80s, multi-link rear suspension is increasingly used in modern sedans and coupes. The earliest applicants include Nissan 200SX, Infiniti Q45, Mercedes S-class and BMW 3-Series etc. It is difficult to describe its construction because it is not strictly defined. In theory, any independent suspensions having 3 control arms or more are multi-link. Different designs may have very different geometry and characteristic, for example, BMW's multilink looks like a letter "Z", thus gave its name

"Z-axle". It is relatively space-engaging but offers very good handling; Honda Accord's multi-link is essentially a double wishbones suspension added with the fifth control arm. Audi A4's Quadralink front suspension has four links. It looks alike double wishbones but eliminates torque steer.



<< Honda Accord's 5-link rear suspension

It is too early to say whether multi-link suspension offer handling on a par with double wishbones. Most sports cars and all the best racing cars still use double wishbones. Only Porsche 993 and 996, Nissan Skyline GT-R etc. chose multi-link instead. However, it seems that multi-link can offer better compromise between handling and space efficiency, as more and more sedans adopt it. Honda, which used to be a loyal supporter of double wishbones, shifted to multi-link setup in the latest Accord could be an evidence.

Advantage: Good handling and ride.

Disadvantage: Not as cheap and as compact as MacPherson and Torsion beam.

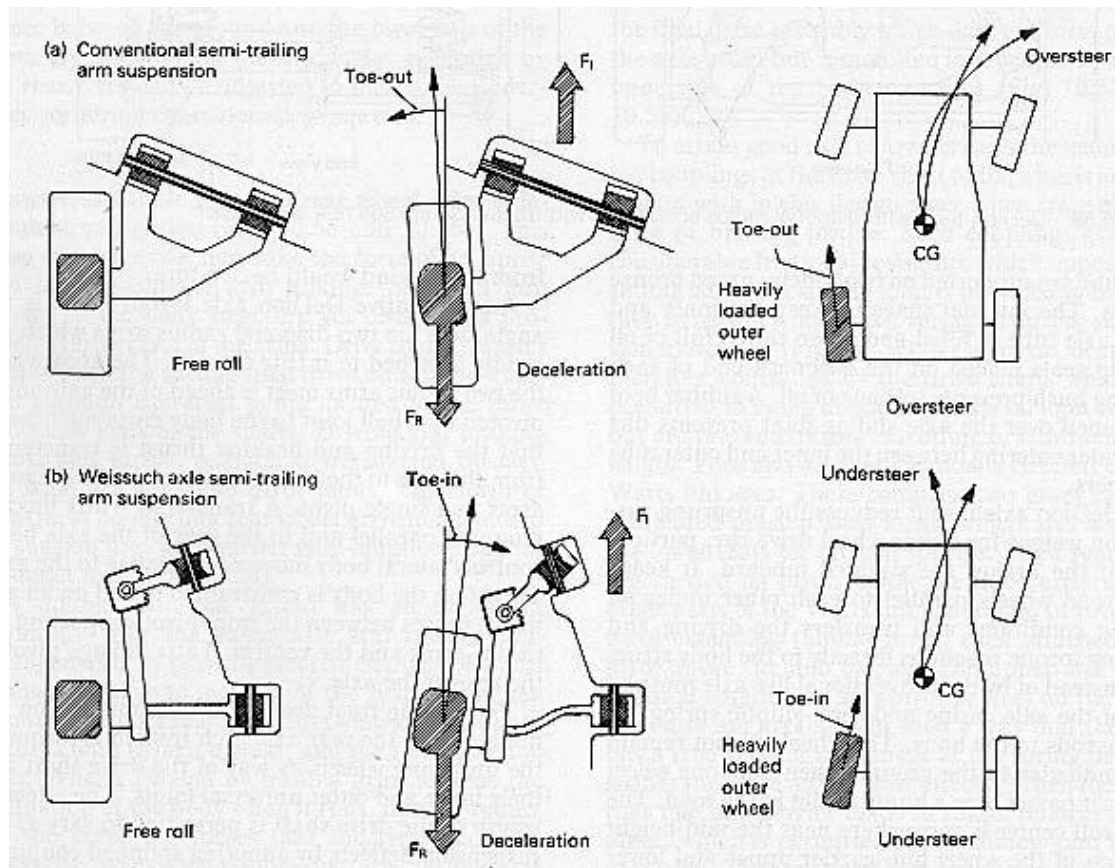
Who use it ? Mid-size to luxurious sedans.

Weissach axle suspension

In the mid-70s, Porsche developed this unique rear suspension for its award-winning 928. Basically it is a variant of semi-trailing arm suspension.

In any suspensions, the pivot joints must be inserted with rubber bushing to absorb noise and vibration. For conventional semi-trailing arm suspension (first row in the following picture), whenever under braking, the momentum of the car body tries to pull the car "away" from the rear suspension. Due to the elasticity of the rubber bushing, the rear wheel will toe-out. As a result, the car will oversteer.

Weissach axle was designed to eliminate this oversteer (second row in the picture). By splitting one trailing link into two pieces, with a pivot joint added between them, the oversteer under braking can be eliminated or even introduce some understeer ! This help stablizing the cornering motion. Some people call it as "passive rear-wheel steering".



Who use it ? Porsche 928.

Sub-frame mounting



Reduction of NVH (Noise, Vibration and Harshness) is a very important issue for modern cars. Conventional suspensions are mounted directly to the chassis (though via rubber bushing) so that NVH can be easily transmitted to the cabin. One of the popular solutions is to mount the suspension onto a sub-frame (still via bushing), which is usually made of aluminium alloy or is produced by hydroforming to minimize the addition of weight. The sub-frame itself can absorb some of the NVH. It is in turn mounted to the body by more bushings, thus reduce NVH further. The picture shows Porsche 993's rear suspension with sub-frame. Today, sub-frame mounting is no longer exclusive for high-price cars. The latest Opel Astra and VW Golf have sub-frame mounting too, so do many GM mainstream models.

Adaptive Suspensions

Adaptive damping

Ferrari and Maserati are the keenest users of adaptive damping. The former's Mondial T, F355, 456GT, 550M, 360M and the latter's Shamal, Quattroporte and 3200GT all employed electronic adjustable dampers in the suspensions. In most of the time, the damper is in "soft" setting to benefit ride comfort. In case the car goes in action, it is set to "stiff" mode for stable handling and minimize body roll.

The mechanism is usually very simple. By varying the total area of valves area within the shock absorber, different rate of damping can be obtained. Therefore the shock absorber alone is able to implement the adaptive damping.



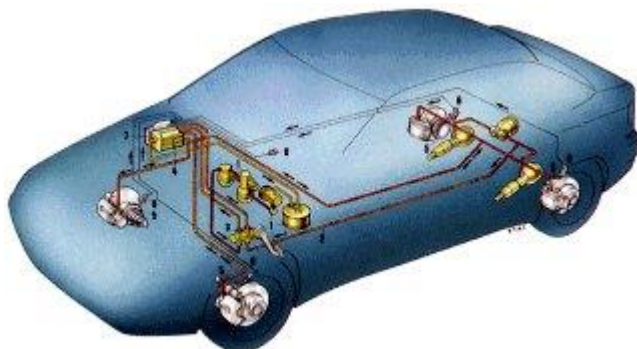
Ferrari Mondial T - the earliest Ferrari to have adaptive damping.

Ferrari's earliest system was launched in Mondial T. It required the driver to select the rate of damping among 3 settings - soft, intermediate and hard. Later, in 456GT and F355's systems, computer decided the setting automatically. Sensors were employed to measure the longitudinal acceleration, lateral acceleration, speed, brake pressure, load and steering angle. Via analysing these data, the computer knew the driver's intention - to go fast or to travel leisurely. Then decide the most suitable damper setting.

It looks great, but the effectiveness is quite limited. Firstly, it can just vary the damping rate, not the spring rate and anti-roll bar function. Secondly, individual wheel or axle cannot be set according to need. All four wheels always run on the same damping setting. Thirdly, it seems that until now all the designs still react slowly, therefore they are employed to deal with the changing driving style (which is more consistent) rather than the change of road condition (which is fast-changing and unpredictable).

Semi-Active Suspension

Citroen XM's Hydractive



XM's Hydractive system. Note that there are totally 3 spheres in the rear axle. All the suspensions are interconnected with high-pressure hydraulic which is supplied by the engine-driven pump. The front spheres are not shown in this picture.

Unlike adaptive damping, Citroen's famous Hydractive suspension is fast-reacting, can vary individual axles' spring rate and damping rate. Let's see how it works:

The Hydractive, which appeared in the XM as optional equipment since 1989, was based on the company's traditional "Hydropneumatic suspension". The latter has a large sphere at the top of each

shock absorber. Within the sphere there are 2 compartments filling with compressed air and high-pressure fluid respectively, separated by an elastic barrier. The gas acts as conventional suspensions' spring while the fluid acts as damper. Shock from the wheel transmit via the fluid into the elastic barrier, than compress into the gas compartment. The gas absorbs the energy and release back to the fluid, which smooth the reaction by its damping effect. Remember, in the "Hydropneumatic suspension" there is no spring and damper. The sphere does the jobs of both.

Now comes to the sophisticated Hydractive suspension. It still employs the spheres at each corner, but added with an extra sphere (central sphere) at each of the axles, linking by fluid between the spheres at left and right wheel. The front and rear central spheres also link each other. In other words, the front and rear, left and right suspensions are all interconnected by high-pressure fluid.

With the addition of central spheres, the total volume of gas and fluid increases. Therefore the suspension can provide softer spring and damping rate that requires by comfortable ride. Moreover, like the conventional Hydropneumatic suspension, the fluid can flow from one wheel to another, one axle to another, thus further smoothen the ride.

When the car need stable handling and roll resistance, valves in the central spheres close, thus isolating the wheel's spheres. As the volume of gas and fluid has been reduced, stiffer spring and damping rate are obtained.

The setting is not just bounded to "soft" and "hard" only, since there are many valves associated in the central spheres. The more valves close, the stiffer the suspension becomes. In fact, Citroen added more valves to the Hydractive 2 system in 1993 in order to create more level of setting and smoother transition between soft and hard.

What made the Hydractive so effective is its fast-reacting brainpower. Powerful computer analysis the data acquired by speed, g-force, throttle, brakes and gearbox sensors, then decide the most suitable setting and activate the valves via solenoid and sophisticate power electronics.

Because the energisation of the solenoid valves takes as long as half a second while de-energisation need merely 2 milliseconds, Citroen use the de-energisation to actuate the closure of valves, thus making the change from soft to hard setting far quicker than vice versa. This is very logical, as we always need stiff suspensions as soon as we start driving hard. We don't need to enjoy comfortable ride as soon as we ease off the throttle.

Citroen C5's Hydractive 3

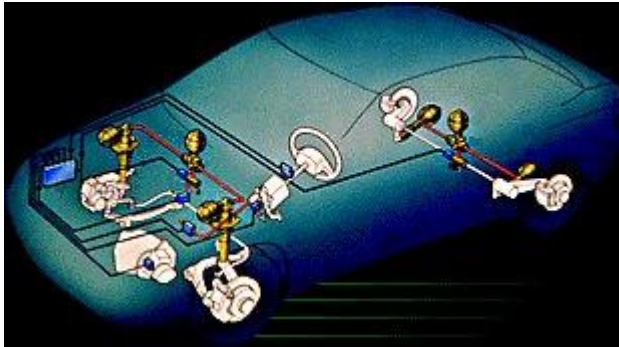
The third generation of Hydractive suspension is relatively simple to explain. The system, introduced in C5 in early 2001, was a refinement of the previous generation. Unlike Activa (Hydractive 2), it does not have the active anti-roll bar which was criticized by some as feeling unnatural. Instead, it added variable ride height function, which is easily to implement in hydraulic suspension. By adding or removing fluid in the suspension, ride height can be varied. At speed, ride height will be decreased to reduce aerodynamic drag and improve stability. By lowering the front end a few mm more than the rear also introduce some more downforce (well, may be less lift). At low speed, ride height will be increased to provide more bump travel and avoid contacting with ground obstacle. Off road at really low speed the ride height will be adjusted to maximum.

The best of the Hydractive 3, however, is the recalibration of the software system to provide firmer yet smoother cornering without the nervous reaction of the previous generations. Moreover, by reshaping the gas-fluid spheres, the system becomes more durable, without needing maintenance until 200,000 km or 5 years.

As before, electronics sensors monitor steering action, brake pedal pressure, engine speed etc. to know the driver's driving style. If it sense a leisure driving style, electromagnetic valves will be opened thus link the center sphere of each axle with left and right suspension spheres, hence increasing volume of gas and fluid thus provides softer spring and damping rate. In contrast, for sporty driving style the center sphere will be isolated from suspension spheres thus increase spring and damping rate, providing a firmer ride and better body control.

Active Roll Control

Citroen Xantia's Activa



Xantia Activa has even more spheres. Note the additional sphere incorporated in the front anti-roll bar.

Compare with XM's Hydractive suspension, Xantia's Activa system has an additional anti-roll function.

Hydractive reduce body roll by stiffening the spring and damper in the price of ride. If it could stiffen the suspensions to as hard as Formula One racing cars, it would have achieve near-zero body roll under hard cornering. However, because we need an acceptable level of ride comfort in a road car, we cannot do that. Therefore Citroen developed the active anti-roll bar, added it to the Hydractive and becomes Xantia's Activa system.

Based on the Hydractive, Activa incorporates a gas-filled sphere in the middle of the anti-roll bar. The anti-roll bar is unusually thick at a diameter of 28 mm up front and 25 mm at the rear. The sphere acts as a cushion, thus allows the anti-roll bar to be twisted more easily. Therefore, the 28 mm anti-roll bar actually performs like a 23 mm one, thus offer less anti-roll function for normal drive. When the car goes into a corner quickly, computer detects body roll thus close the valves in the sphere. This isolate the gas in the sphere thus eliminate the cushion effect. The anti-roll bar thus resume its original stiffness, acting exactly as a 28 mm anti-roll bar.

It doesn't end here. If the lateral acceleration is so strong that body roll continues to exceed 0.5 degree, fluid will be fed into 2 hydraulic rams at the front and rear which adjust the anti-roll bars to keep cornering level.

At any time, Xantia Activa rolls at most half a degree. This make it not only spectacular to look at, but also improve cornering speed. French magazine L'Automobile tested a Xantia Activa on skidpad and measured an amazing 0.94 g lateral acceleration. This compares competitively with many supercars - NSX managed 0.93 g, Ferrari 512TR 0.92 g, Toyota Supra 0.95 g and Ferrari F40's 1.01 g. This is even more impressive if you consider the Xantia wears just 205/55R15 tyres ! Most cars in its class manage around 0.8 g only !



<< Xantia Activa cornering without roll

Mercedes' Active Body Control (ABC)

Compare with Citroen's Activa, Mercedes' ABC (Active Body Control) seems rather simple. ABC is a purely active roll control device. It can vary spring rate but not damping, unlike Citroen's Hydractive or Activa. Therefore it is not classified as semi-active suspension. However, the application in the new CL coupe demonstrate it helps achieving a stable and fluent cornering. It also saves the need of anti-roll bar.



New CL with ABC versus old CL

The mechanical is quite simple. Each of the four wheels rides on a thick strut which incorporate both spring and damper into a single unit. The damper is in the core of the strut, surrounding by the coil spring which is topped by a fluid chamber. When the chamber is fully filled with fluid (supplied from hydraulic pump), the spring is pushed towards the wheel and compressed, thus resist body roll. On the contrary, if the fluid chamber is emptied, the spring will be released towards the top of the strut, thus become softer.



ABC is not very fast-reacting - the maximum frequency of change is just 5 Hz, because the filling of fluid takes time - but that's more than enough for dealing with body roll.

Lotus' fully active suspension

Unquestionably, active suspension is the most ideal suspension. A true active suspension has double-acting hydraulic actuator instead of springs and dampers. As tyres meets bump, the wheel's acceleration and vertical load is transmitted to a computer which calculates the required wheel velocity and displacement and sends control signal to the actuator. As the dialogue is conducted hundreds of times a second, the wheel accurately follows the contour of a bump, thus protecting the body structure against unwanted forces.

When riding on a bump, Active suspension, Hydractive suspension and Adaptive damping react very differently. The following explain how they "think":

Adaptive damping : "A shock encountered ! Another shock ! Again another Oh, it seems that the car is running slowly on bumpy road, let me change the damping rate to soft setting."

Hydractive suspension : "A shock encountered ! I must be riding on a bump. As the car is running slowly, I must change the suspension to soft-intermediate setting OK, I've changed Oh, the body still accelerating upward ! This means the suspension is still too hard. I should have changed to soft setting ! It's too late. The bump has already been passed."

Active suspension : "A shock is encountered ! I start riding on a bump. Vertical acceleration sensor and speed sensor tells me the bump is quite high. OK, signal the wheel actuator to compress 10 mm progressively sensors tell me it's not enough. Well, this time compress another 8 mm and see what's going on 6 mm this time 4 more mm 3 2 1 Wow ! I am riding on the peak right now ! Start releasing the actuator for 1 mm 2 mm 4 mm 7 mm 10 mm Return to flat ground ! Well done !"

As you can see, active suspension is simply a perfect concept. Theoretically it could absorb all the shock while maintaining the car body stable. Engineers dreamed for it long ago, but it was Lotus that put it into reality.

Lotus started researching active suspension in 1981, originally intended to equip its Formula One racing cars. The active F1 ran in Brazil and Long Beach '83 in the hands of Nigel Mansell. Despite of lacking competitiveness, it proved that active suspension could withstand hard use at 180 mph and 3 g lateral acceleration. The development team went back to drawing board and did more test to improve the software. It was not raced again until 1987, when the Honda-powered 99T won 3 races in the hands of Ayrton Senna.

However, the active suspension did not offer sufficient advantage in F1 racing. Theoretically, it could raise cornering speed considerably. ("Cornering at 200mph" used to Team Lotus's slogan when defending this technology.) But on the down side, its hydraulic pump consumed horsepowers. I don't have the exact figure, but years later Lotus told us the active suspension in its Excel development car consumed 4 - 4.5 hp on smooth road and up to 9 hp on rough road. Worst of all, Team Lotus did not get specially developed tyres to extract its potential. As the active suspension reduced tyre's slip angle, the tyres generated insufficient heat to attain the necessary working temperature.

Just after the F1 debut in the 1983 season, Lotus Engineering started developing the active suspension technology for production car use. It used the Esprit as the development platform. Like the racing car, the hardware - hydraulic actuators - came from aerospace industry, where active suspension was used in advanced jet engines. According to the engineers involved, the most crucial part was the software rather than hardware. They had to road test a lot to acquire the necessary data in order to write the program.

The first 2 generations were springless, but the Mk III and Mk IV system, which were equipped in the Excel development cars, had springs as back up in case the active system break. The software was gradually improved. British magazine Fastlane tested them twice, once in the '87 Mk III and then in the Mk IV two years later. In the latter it reported significant improvement in ride quality and body control. It also expressed full optimistic that the system would go into mass production within a few years, probably under the name Volvo, Chevrolet or Mercedes-Benz, as they all had been consulting Lotus.

This did not come true. Until today I haven't seen any sign that car makers are going to put a fully active suspension into production. The main reasons, I guess, are likely to be cost, power consumption and reliability. The only successful application was still in motor racing - between 1992 and 1994, F1 championship were dominated by the active Williams and Benetton. Meanwhile, DTM series also saw active suspension's superiority in Mercedes C-class and Opel Calibra. Perhaps it was too superior, FIA eventually banned it.

The last time I heard Active suspension was in 1995 (?), when Lotus showed the Esprit SDIII development car. After that, the automotive world seems to have forgotten the most ideal suspension ever appeared.

Some people was misled by Nissan Infiniti Q45a of 1990. Nissan called the car's suspension as "Fully Active" but that was actually a lie. It was just an adaptive damping, with conventional coil springs taking care of compression and an hydraulic device dealing with rebound.

Transmission Systems

Bearings

The bearing makes many of the machines we use every day possible. Without bearings we would be constantly replacing parts that wore out from friction. The concept behind a bearing is very simple: Things roll better than they slide. The wheels on your car are like big bearings. If you had something like skis instead of wheels your car be a lot more difficult to push down the road. That is because when things slide the [friction](#) between them causes a force that tends to slow them down. But if the two surfaces can roll over each other then the friction is greatly reduced. Bearings do this by

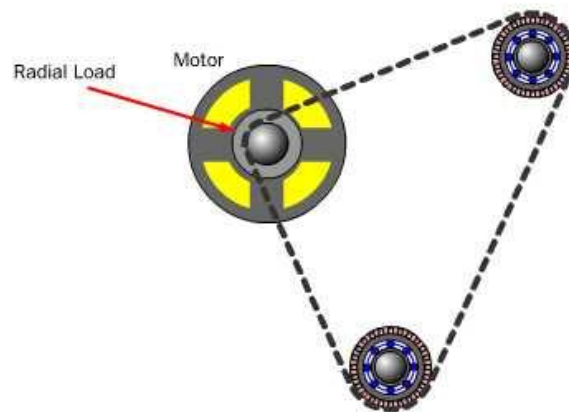


A tapered roller bearing from a manual transmission

providing smooth metal balls or rollers, and a smooth inner and outer metal surface for the balls to roll against. These balls or rollers "bear" the load, allowing the device to spin smoothly.

Bearing Loads

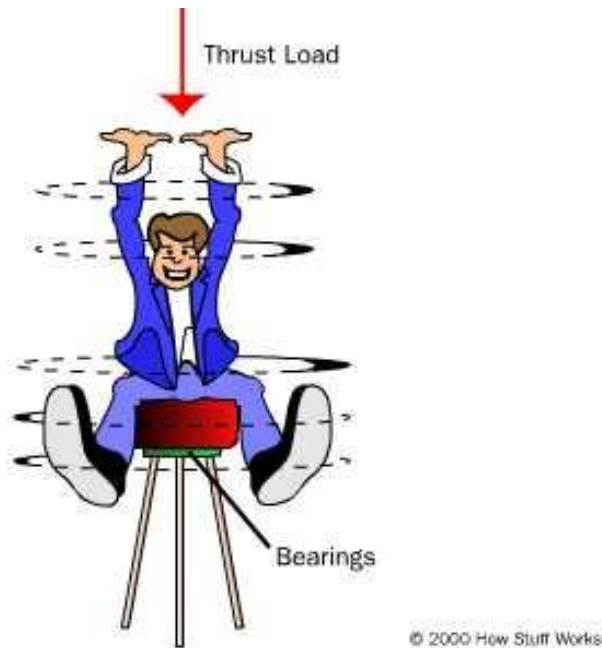
Bearings typically have to deal with two kinds of loading, **radial** and **thrust**. Depending on where the bearing is being used it may see all radial loading, all thrust loading or a combination of both.



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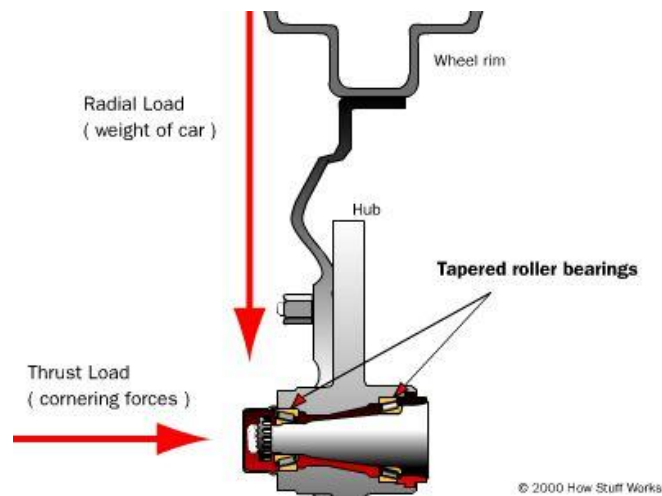
The bearings that support the shafts of motors and pulleys are subject to a radial load

The bearings in the electric motor and the pulley above face only a radial load. In this case, most of the load comes from the tension in the belt connecting the two pulleys.



The bearings in this stool are subject to a thrust load

The bearing above is like the one in a barstool. It is loaded purely in thrust, and the entire load comes from the weight of the person sitting on the stool.



The bearings in a car wheel are subject to both thrust and radial loads

The bearing above is like the one in the hub of your car wheel. This bearing has to support both a radial load and a thrust load. The radial load comes from the weight of the car, the thrust load comes from the cornering forces when you go around a turn.

Types of Bearings

There are many types of bearings, each used for different purposes. These include ball bearings, roller bearings, ball thrust bearings, roller thrust bearings and tapered roller thrust bearings.

Ball Bearings

Ball bearings, as shown in **Figure 5**, are probably the most common type of bearing. They are found in everything from inline skates, to hard drives. These bearings can handle both radial and thrust loads, and are usually found in applications where the load is relatively small. In a ball bearing, the load is transmitted from the outer race to the ball, and from the ball to the inner race. Since the ball is a sphere, it only contacts the inner and outer race at a very small point, which helps it spin very smoothly. But it also means that there is not very much contact area holding that load, so if the bearing is overloaded the balls can deform or squish, ruining the bearing.



Photo courtesy [The Torrington Company](#)

Figure 5. Cutaway view of a ball bearing

Roller Bearings

Roller bearings, like the one illustrated in **Figure 6**, are used in applications like conveyor belt rollers where they must hold heavy radial loads. In these bearings, the roller is a cylinder, so the contact between the inner and outer race is not a point but a line. This spreads the load out over a larger area allowing the bearing to handle much greater loads than a ball bearing. However this type of bearing is not designed to handle much thrust loading. A variation of this type of bearing, called a **needle bearing**, uses cylinders with a very small diameter. This allows the bearing to fit into tight places.



Photo courtesy [The Torrington Company](#)

Figure 6. Cutaway view of a roller bearing

Ball Thrust Bearing

Ball thrust bearings, like the one in **Figure 7**, are mostly used for low speed applications and cannot handle much radial load. Barstools and lazy Susan turntables use this type of bearing.

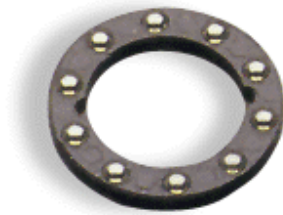


Photo courtesy [The Torrington Company](#)

Figure 7. Ball thrust bearing

Roller Thrust Bearing

Roller thrust bearings, like the one illustrated in **Figure 8**, can support large thrust loads. They are often found in gearsets like car transmissions between gears, and between the housing and the rotating shafts. The helical gears used in most transmissions have angled teeth, this causes a thrust load which must be supported by a bearing.



Photo courtesy [The Torrington Company](#)

Figure 8. Roller thrust bearing

Tapered Roller Bearings

Tapered roller bearings can support large radial and large thrust loads. Tapered roller bearings are used in car hubs where they are usually mounted in pairs facing opposite directions, so that they can handle thrust in both directions.



Photo courtesy [The Torrington Company](#)
Figure 9. Cutaway view of a tapered roller bearing and a double tapered roller bearing

Gears

You see [gears](#) in just about everything that has spinning parts. For example, car engines and [transmissions](#) contain lots of gears. If you ever open up a [VCR](#) and look inside, you will see it is full of gears. Wind-up, grandfather and pendulum [clocks](#) contain plenty of gears, especially if they have bells or chimes. You probably have a power meter on the side of your house, and if it has a see-through cover, you can see that it contains 10 or 15 gears. Gears are everywhere where there are [engines](#) and [motors](#) producing rotational motion.

Using Gears

Gears are generally used for one of four different reasons:

1. To reverse the direction of rotation
2. To increase or decrease the speed of rotation
3. To move rotational motion to a different axis
4. To keep the rotation of two axis synchronized

You can see effects 1, 2 and 3 in the figure above. In this figure, you can see that the two gears are rotating in opposite directions, that the smaller gear is spinning twice as fast as the larger gear, and that the **axis of rotation** of the smaller gear is to the right of the axis of rotation for the larger gear. The fact that one gear is spinning twice as fast as the other results from the **ratio** between the gears, or the **gear ratio**. In this figure, the diameter of the gear on the left is twice that of the gear on the right. The gear ratio is therefore 2:1 (pronounced "two to one"). If you watch the figure you can see the ratio: Every time the larger gear goes around once, the smaller gear goes around twice. You can see that if both gears had the same diameter, they would rotate at the same speed but in opposite directions.

The Concept of Gear Ratio

Understanding the concept of the gear ratio is easy if you understand the concept of the **circumference** of a circle. Keep in mind that the circumference of a circle is equal to the diameter of the circle multiplied by [Pi](#) (Pi is equal to 3.14159...). Therefore, if you have a circle or a gear with a diameter of one inch, the circumference of that circle will be 3.14159 inches. The following figure shows how the circumference of a circle with a diameter of 1.27 inches is equal to a linear distance of 4 inches:

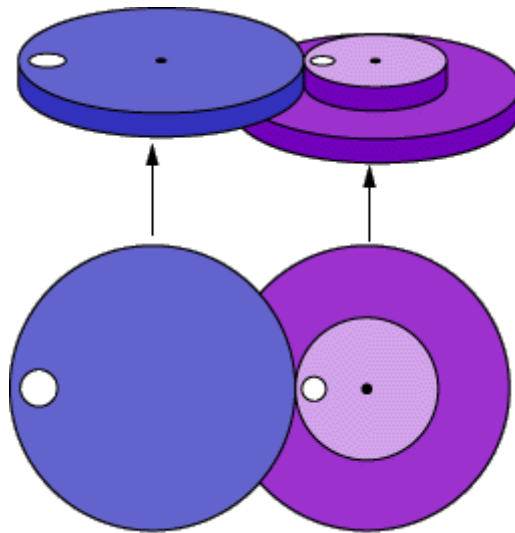
Let's say that you had another circle whose diameter was $1.27 \text{ inches} / 2 = 0.635 \text{ inches}$, and you rolled it in the same way as in this figure. You would find that, because its diameter is one half of the circle's in the figure, it has to complete two full rotations to cover the same 4 inch line. This explains why two gears, one half as big as the other, have a gear ratio of 2:1. The smaller gear has to spin twice to cover the same distance covered when the larger gear spins once.

Most [gears](#) that you see in real life have teeth. The teeth have three advantages:

1. They prevent slippage between the gears - therefore axles connected by gears are always synchronized exactly with one another.
2. They make it possible to determine exact gear ratios - you just count the number of teeth in the two gears and divide. So if one gear has 60 teeth and another has 20, the gear ratio when these two gears are connected together is 3:1.
3. They make it so that slight imperfections in the actual diameter and circumference of two gears don't matter. The gear ratio is controlled by the number of teeth even if the diameters are a bit off.

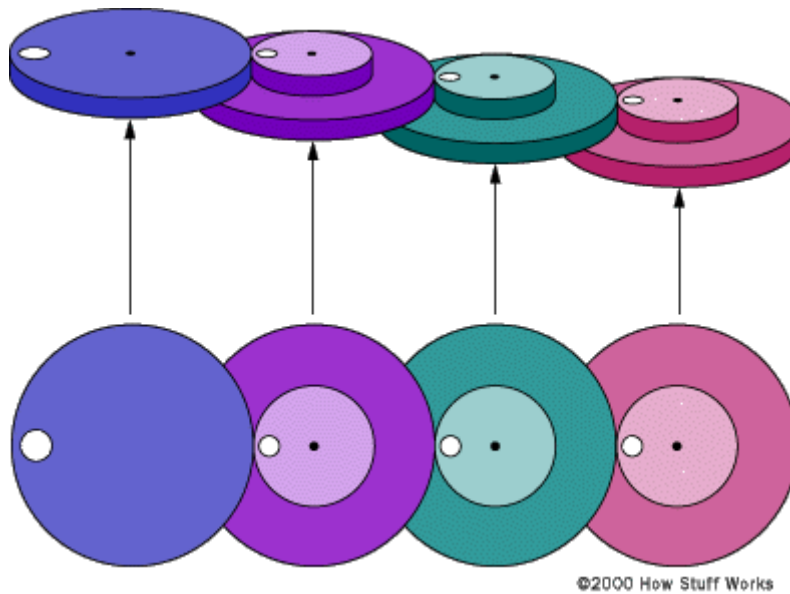
Gear Trains

To create large gear ratios, gears are often connected together in **gear trains**, as shown here:

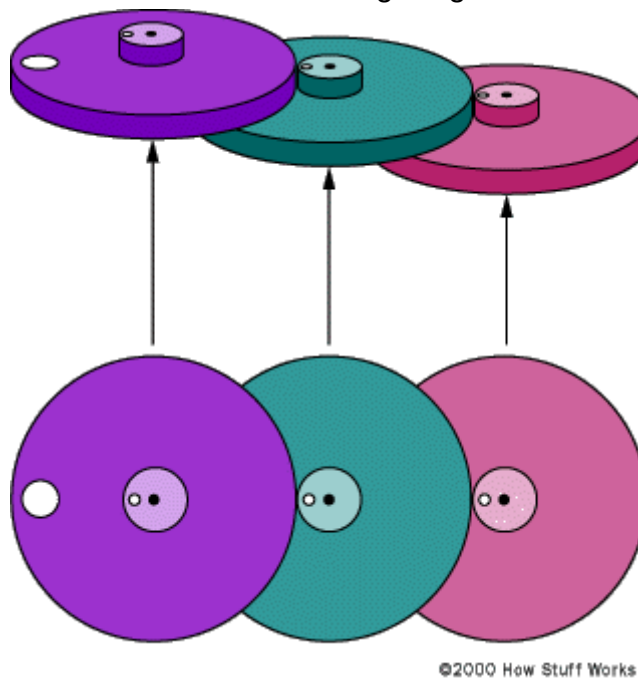


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The right-hand (purple) gear in the train is actually made in two parts, as shown. A small gear and a larger gear are connected together, one on top of the other. Gear trains often consist of multiple gears in the train, as shown in the following two figures:



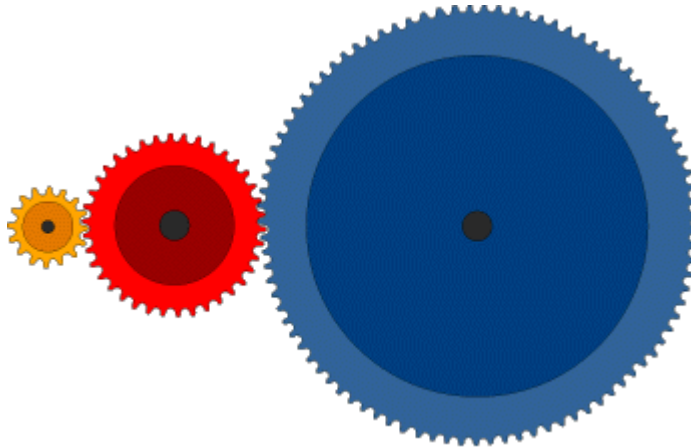
In the case above, the purple gear turns at a rate twice that of the blue gear. The green gear turns at twice the rate as the purple gear. The red gear turns at twice the rate as the green. The gear train shown below has a higher gear ratio:



In this train, the smaller gears are one-fifth the size of the larger gears. That means that if you connect the purple gear to a motor spinning at 100 rpm (revolutions per minute), the green gear will turn at a rate of 500 rpm and the red gear will turn at a rate of 2,500 rpm. In the same way, you could attach a 2,500 rpm motor to the red gear to get 100 rpm on the purple gear. If you can see inside your power meter and it is of the older style with five mechanical dials, you will see that the five dials are connected to one another through a gear train like this, with the gears having a ratio of 10:1. Because the dials are directly connected to one another, they spin in opposite directions (you will see that the numbers are reversed on dials next to one another).

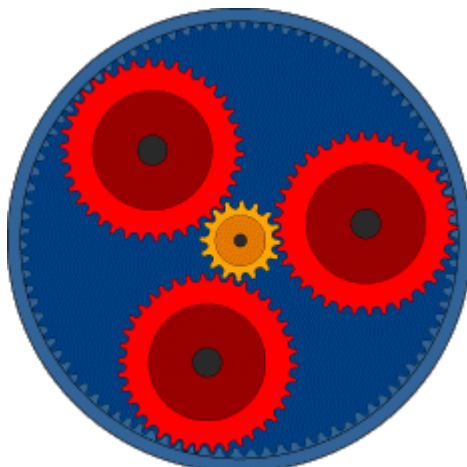
Other Uses for Gears

There are many other ways to use gears. One specialized gear train is called a **planetary gear train**. Planetary gears solve the following problem. Let's say you want a gear ratio of 6:1 with the input turning in the same direction as the output. One way to create that ratio is with the following three-gear train:



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In this train, the blue gear has six times the diameter of the yellow gear (giving a 6:1 ratio). The size of the red gear is not important because it is just there to reverse the direction of rotation so that the blue and yellow gears turn the same way. However, imagine that you want the axis of the output gear to be the same as that of the input gear. A common place to need this same-axis capability is in an [electric screwdriver](#). In that case, you can use a planetary gear system, as shown here:



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In this gear system, the yellow gear (the sun) engages all three red gears (the planets) simultaneously. They are all three attached to a plate (the planet carrier), and they engage the *inside* of the blue gear (the ring) instead of the outside. Because there are three red gears instead of one, this gear train is extremely rugged. The output shaft is attached to the blue ring gear, and the planet carrier is held stationary - this gives the same 6:1 gear ratio.

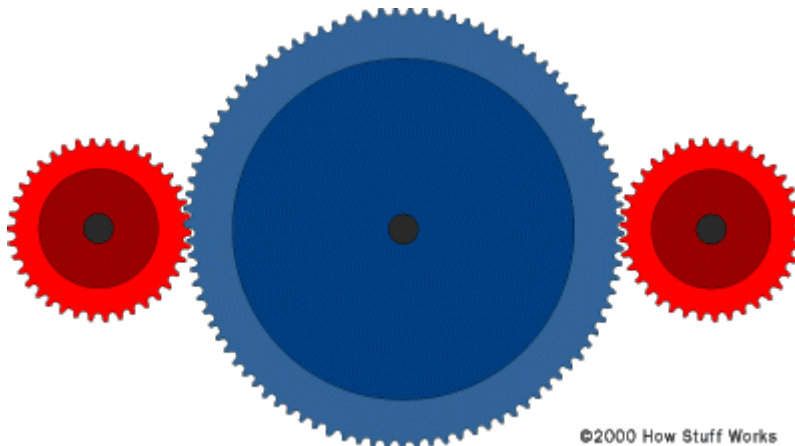
Another interesting thing about planetary gearsets is that they can produce different gear ratios depending on what gear you use as the input, which gear you use as the output, and which one you hold still. For instance if the input is the sun gear, and we hold the ring gear stationary, and attach the output shaft to the planet carrier we get a different gear ratio. In

this case the planet carrier and planets orbit the sun gear, so instead of the sun gear having to spin six times for the planet carrier to make it around once, it has to spin seven times. This is because the planet carrier circled the sun gear once in the same direction as it was spinning, subtracting one revolution from the sun gear. So in this case we get a 7:1 reduction.

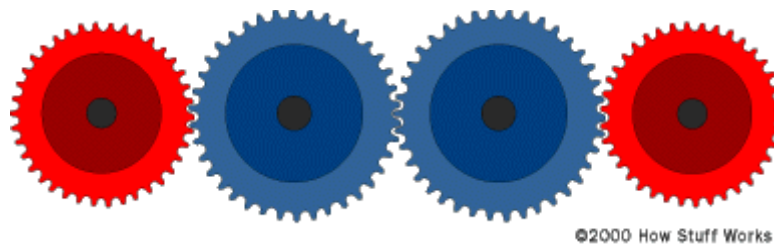
You could rearrange things again, and this time hold the sun gear stationary, take the output from the planet carrier, and hook the input up to the ring gear. This would give you a 1.17:1 gear reduction. An automatic transmission uses planetary gearsets to create the different gear ratios by using clutches and brake bands to hold different parts of the gearset stationary, and change the inputs and outputs.

Example

Finally, imagine the following situation: you have two red gears that you want to keep synchronized, but they are some distance apart. You can place a big gear between them if you want them to have the same directions of rotation:



Or you can use two equal-sized gears if you want them to have opposite rotational direction:



However, in both of these cases the extra gears are likely to be heavy and you need to create axles for them. In these cases the common solution is to use either a **chain** or a **toothed belt**, as shown here:



The advantages of chains and belts are light weight, the ability to separate the two gears by some distance, and the ability to connect many gears together on the same chain or

belt. For example, in a car [engine](#), the same toothed belt might engage the crankshaft, two camshafts and the alternator. If you had to use gears in place of the belt, it would be a lot harder!

Gears are used in tons of mechanical devices. They do several important jobs, but most important, they provide a [gear reduction](#) in motorized equipment. This is key because, often, a small motor spinning very fast can provide enough [power](#) for a device, but not enough [torque](#). For instance, an electric screwdriver has a very large gear reduction because it needs lots of torque to turn screws, but the motor only produces a small amount of torque at a high speed. With a gear reduction, the output speed can be reduced while the torque is increased. Another thing gears do is adjust the direction of rotation. For instance, in the differential between the rear wheels of your car, the power is transmitted by a shaft that runs down the center of the car, and the differential has to turn that power 90 degrees to apply it to the wheels.

On any gear, the [ratio](#) is determined by the distances from the center of the gear to the point of contact. For instance, in a device with two gears, if one gear is twice the size of the other, the ratio would be 2:1. One of the most primitive types of gears we could look at would be a wheel with wooden pegs sticking out of it.

The problem with this type of gear is that the distance from the center of each gear to the point of contact changes as the gears rotate. This means that the gear ratio changes as the gear turns, meaning that the output speed also changes. If you used a gear like this in your car, it would be impossible to maintain a constant speed -- you would be accelerating and decelerating constantly. Many modern gears use a special tooth profile called an **involute**. This profile has the very important property of maintaining a constant speed ratio between the two gears. Like the peg wheel above, the contact point moves; but the shape of the involute gear tooth compensates for this movement.



Photo [Emerson Power Transmission Corp.](#) courtesy

Gear Types

Spur Gears

Spur gears are the most common type of gears. They have straight teeth, and are mounted on parallel shafts. Sometimes, many spur gears are used at once to create very large gear reductions.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 2. Spur gears

Spur gears are used in many devices that you can see all over How Stuff Works, like the [electric screwdriver](#), [dancing monster](#), [oscillating sprinkler](#), [windup alarm clock](#), [washing machine](#), [clothes dryer](#) and [Caterpillar Challenger Tractor](#). But you won't find many in your car.

This is because the spur gear can be really loud. Each time a gear tooth engages a tooth on the other gear, the teeth collide, and this impact makes a noise. It also increases the stress on the gear teeth.

To reduce the noise and stress in the gears, most of the gears in your car are **helical**.

Helical Gears

The teeth on **helical gears** are cut at an angle to the face of the gear. When two teeth on a helical gear system engage, the contact starts at one end of the tooth and gradually spreads as the gears rotate, until the two teeth are in full engagement.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 3. Helical gears

This gradual engagement makes helical gears operate much more smoothly and quietly than spur gears. For this reason, helical gears are used in almost all car [transmissions](#).

Because of the angle of the teeth on helical gears, they create a thrust load on the gear when they mesh. Devices that use helical gears have [bearings](#) that can support this thrust load.

One interesting thing about helical gears is that if the angles of the gear teeth are correct, they can be mounted on perpendicular shafts, adjusting the rotation angle by 90 degrees.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 4. Crossed helical gears

Bevel gears are useful when the direction of a shaft's rotation needs to be changed. They are usually mounted on shafts that are 90 degrees apart, but can be designed to work at other angles as well. The teeth on bevel gears can be **straight**, **spiral** or **hypoid**. Straight bevel gear teeth actually have the same problem as straight spur gear teeth -- as each tooth engages, it impacts the corresponding tooth all at once.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 5. Bevel gears

Just like with spur gears, the solution to this problem is to curve the gear teeth. These spiral teeth engage just like helical teeth: the contact starts at one end of the gear and progressively spreads across the whole tooth.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 6. Spiral bevel gears

On straight and spiral bevel gears, the shafts must be perpendicular to each other, but they must also be in the same plane. If you were to extend the two shafts past the gears, they would intersect. The **hypoid gear**, on the other hand, can engage with the axes in different planes.

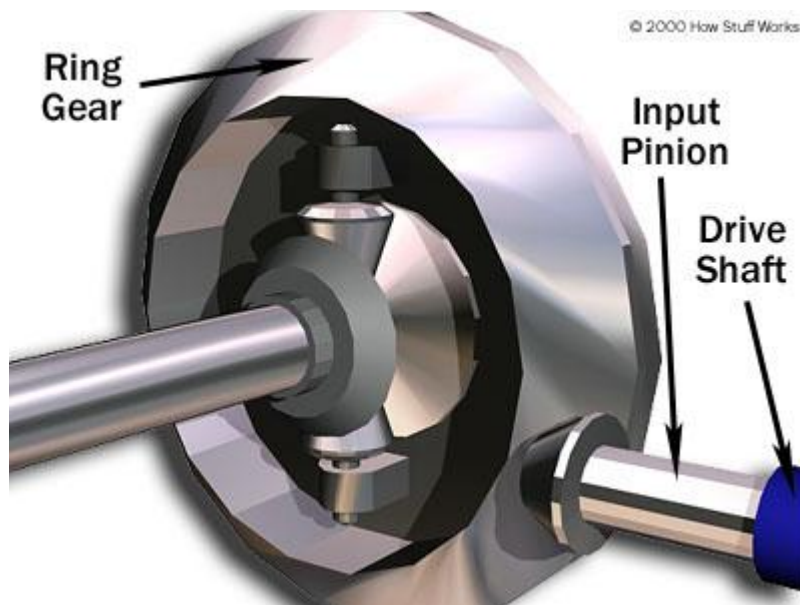


Figure 7. Hypoid bevel gears in a car differential

This feature is used in many car [differentials](#). The ring gear of the differential and the input pinion gear are both hypoid. This allows the input pinion to be mounted lower than the axis of the ring gear. **Figure 7** shows the input pinion engaging the ring gear of the differential. Since the driveshaft of the car is connected to the input pinion, this also lowers the driveshaft. This means that the driveshaft doesn't intrude into the passenger compartment of the car as much, making more room for people and cargo.

Worm gears are used when large gear reductions are needed. It is common for worm gears to have reductions of 20:1, and even up to 300:1 or greater.



Photo courtesy [Emerson Power Transmission Corp.](#)

Figure 8. Worm gear

Many worm gears have an interesting property that no other gear set has: the worm can easily turn the gear, but the gear cannot turn the worm. This is because the angle on the worm is so shallow that when the gear tries to spin it, the friction between the gear and the worm holds the worm in place.

This feature is useful for machines such as conveyor systems, in which the locking feature can act as a brake for the conveyor when the motor is not turning. One other very interesting usage of worm gears is in the [Torsen differential](#), which is used on some high-performance cars and trucks.

Rack and pinion gears are used to convert rotation into linear motion. A perfect example of this is the steering system on many cars. The steering wheel rotates a gear which engages the rack. As the gear turns, it slides the rack either to the right or left, depending on which way you turn the wheel.



Figure 9. Rack and pinion gears from a household scale

Details on Involute Gear Profiles

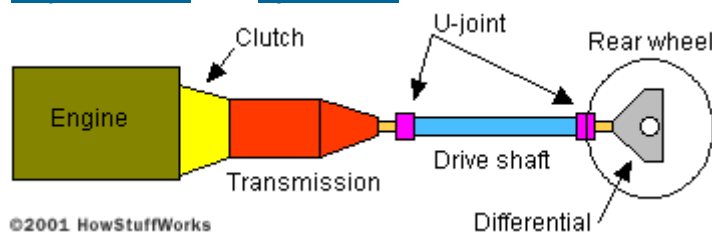
On an **involute profile** gear tooth, the contact point starts closer to one gear, and as the gear spins, the contact point moves away from that gear and toward the other. If you were to follow the contact point, it would describe a straight line that starts near one gear and ends up near the other. This means that the radius of the contact point gets larger as the teeth engage.

The **pitch diameter** is the effective contact diameter. Since the contact diameter is not constant, the pitch diameter is really the average contact distance. As the teeth first start to engage, the top gear tooth contacts the bottom gear tooth inside the pitch diameter. But notice that the part of the top gear tooth that contacts the bottom gear tooth is very skinny at this point. As the gears turn, the contact point slides up onto the thicker part of the top gear tooth. This pushes the top gear ahead, so it compensates for the slightly smaller contact diameter. As the teeth continue to rotate, the contact point moves even further away, going outside the pitch diameter -- but the profile of the bottom tooth compensates for this movement. The contact point starts to slide onto the skinny part of the bottom tooth, subtracting a little bit of velocity from the top gear to compensate for the increased diameter of contact. The end result is that even though the contact point diameter changes continually, the speed remains the same. So an involute profile gear tooth produces a **constant ratio of rotational speed**.

Manual Transmission

Cars need transmissions because of the physics of the [gasoline engine](#). First, any engine has a **redline** -- a maximum rpm value above which the engine cannot go without exploding. Engines have narrow rpm ranges where horsepower and torque are at their maximum. For example, an engine might produce its maximum horsepower at 5,500 rpm. The transmission allows the [gear ratio](#) between the engine and the drive wheels to change as the car speeds up and slows down. You shift gears so the engine can stay below the redline and near the rpm band of its best performance.

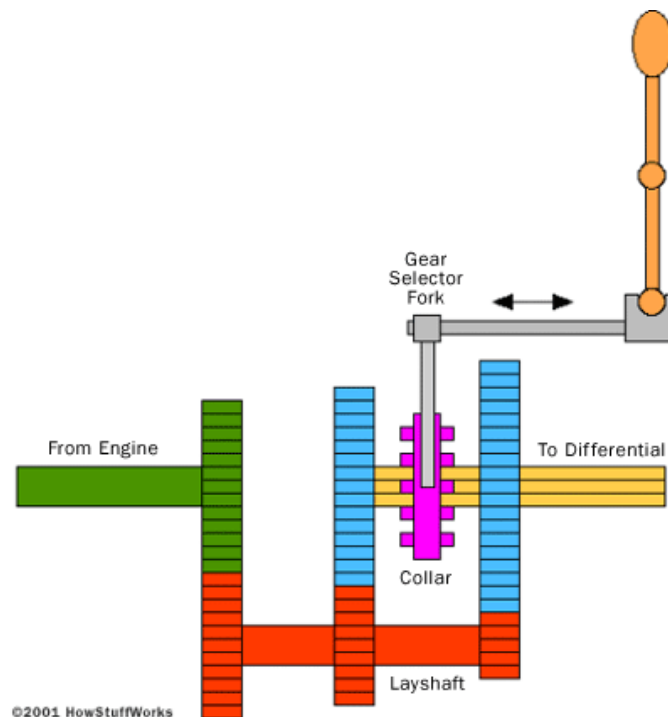
Ideally, the transmission would be so flexible in its ratios that the engine could always run at its single, best-performance rpm value. That is the idea behind the **continuously variable transmission** (CVT). A CVT has a nearly infinite range of gear ratios. However, CVTs have not been able to compete with four-speed and five-speed transmissions in terms of cost, size and reliability, so you usually do not see them in production automobiles. The [Toyota Prius](#) is a [hybrid car](#) that uses a CVT.



The transmission is connected to the engine through the [clutch](#). The input shaft of the transmission therefore turns at the same rpm as the engine. A five-speed transmission applies one of five different gear ratios to the input shaft to produce a different rpm value at the output shaft. Here are some typical gear ratios:

Gear	Ratio	RPM at Transmission Output Shaft with Engine at 3,000 rpm
1st	2.315:1	1,295
2nd	1.568:1	1,913
3rd	1.195:1	2,510
4th	1.000:1	3,000
5th	0.915:1	3,278

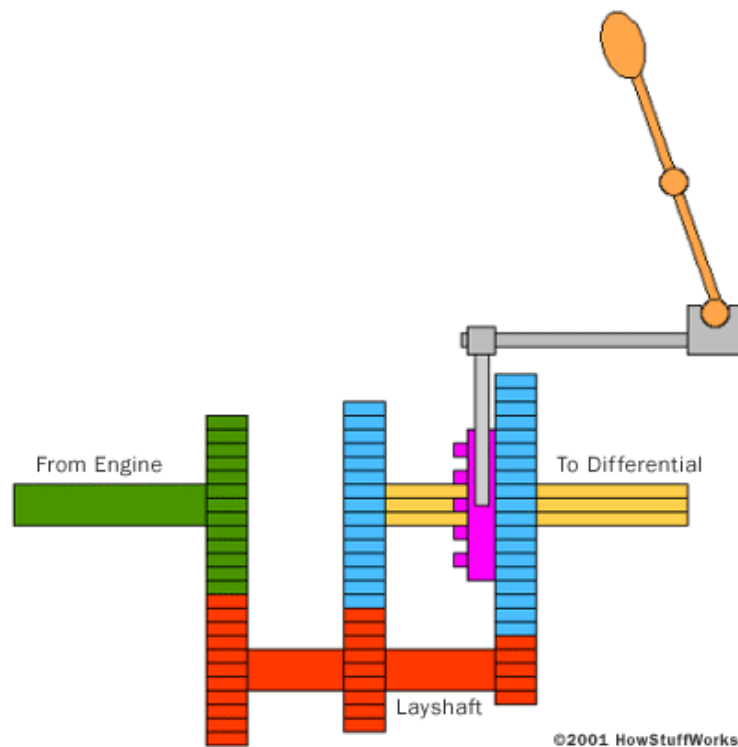
To understand the basic idea behind a standard transmission, the diagram below shows a very simple two-speed transmission in neutral:



Let's look at each of the parts in this diagram to understand how they fit together:

- The green shaft comes from the engine through the [clutch](#). The green shaft and green gear are connected as a single unit. (The clutch is a device that lets you connect and disconnect the engine and the transmission. When you push in the clutch pedal, the engine and the transmission are disconnected so the engine can run even if the car is standing still. When you release the clutch pedal, the engine and the green shaft are directly connected to one another. The green shaft and gear turn at the same rpm as the engine.)
- The red shaft and gears are called the **layshaft**. These are also connected as a single piece, so all of the [gears](#) on the layshaft and the layshaft itself spin as one unit. The green shaft and the red shaft are directly connected through their meshed gears so that if the green shaft is spinning, so is the red shaft. In this way, the layshaft receives its power directly from the [engine](#) whenever the clutch is engaged.
- The yellow shaft is a splined shaft that connects directly to the drive shaft through the [differential](#) to the drive wheels of the car. If the wheels are spinning, the yellow shaft is spinning.
- The blue gears ride on bearings, so they spin on the yellow shaft. If the engine is off but the car is coasting, the yellow shaft can turn inside the blue gears while the blue gears and the layshaft are motionless.
- The purpose of the **collar** is to connect one of the two blue gears to the yellow drive shaft. The collar is connected, through the splines, directly to the yellow shaft and spins with the yellow shaft. However, the collar can slide left or right along the yellow shaft to engage either of the blue gears. Teeth on the collar, called **dog teeth**, fit into holes on the sides of the blue gears to engage them.

The picture below shows how, when shifted into first gear, the collar engages the blue gear on the right:



In this picture, the green shaft from the engine turns the layshaft, which turns the blue gear on the right. This gear transmits its energy through the collar to drive the yellow drive shaft. Meantime, the blue gear on the left is turning, but it is freewheeling on its bearing so it has no effect on the yellow shaft.

When the collar is between the two gears (as shown in the first figure), the transmission is in neutral. Both of the blue gears freewheel on the yellow shaft at the different rates controlled by their ratios to the layshaft.

From this discussion, you can answer several questions:

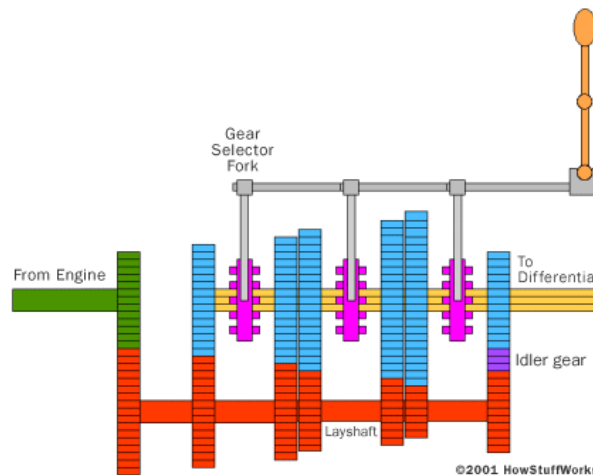
- When you make a mistake while shifting and hear a horrible grinding sound, you are *not* hearing the sound of gear teeth mis-meshing. As you can see in these diagrams, all gear teeth are all fully meshed at all times. The grinding is the sound of the **dog teeth** trying unsuccessfully to engage the holes in the side of a blue gear.
- The transmission shown here does not have "synchros" (discussed later in the article), so if you were using this transmission you would have to **double-clutch** it. Double-clutching was common in older cars and is still common in some modern [race cars](#). In double-clutching, you first push the clutch pedal in once to disengage the engine from the transmission. This takes the pressure off the dog teeth so you can move the collar into neutral. Then you release the clutch pedal and rev the engine to the "right speed." The right speed is the rpm value at which the engine should be running in the next gear. The idea is to get the blue gear of the next gear and the collar rotating at the same speed so that the dog teeth can engage. Then you push the clutch pedal in again and lock the collar into the new gear. At every

gear change you have to press and release the clutch twice, hence the name "double-clutching."

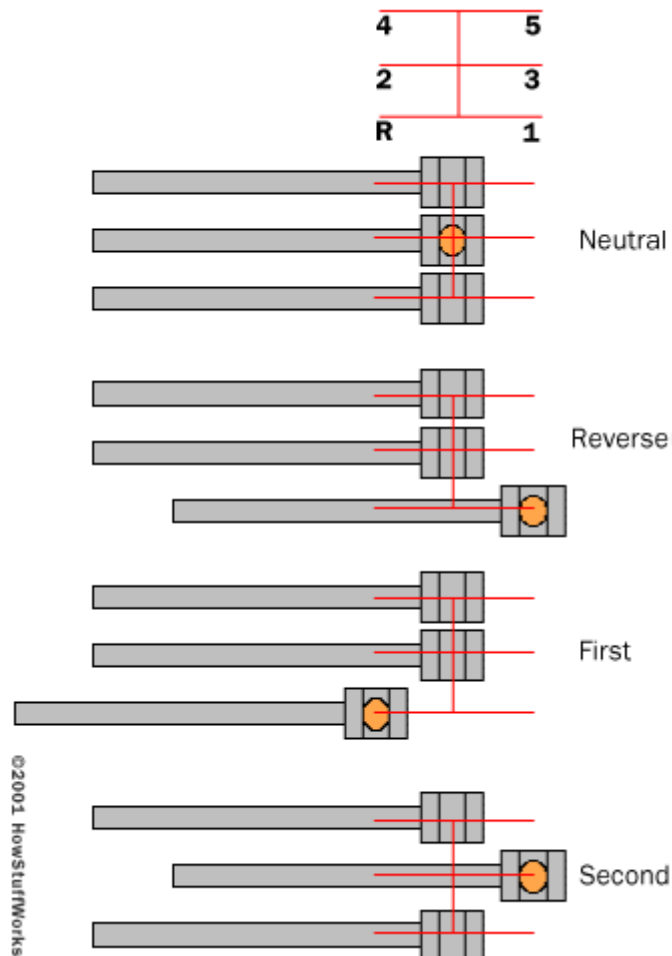
- You can also see how a small linear motion in the gear shift knob allows you to change gears. The gear shift knob moves a rod connected to the fork. The fork slides the collar on the yellow shaft to engage one of two gears.

A Real Transmission

The **five-speed manual transmission** is fairly standard on cars today. It looks something like this internally:

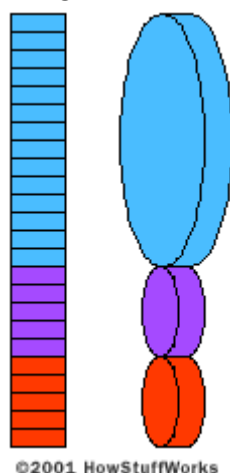


There are three forks controlled by three rods that are engaged by the shift lever. Looking at the **shift rods** from the top, they look like this in neutral, first, second and third gear:



Keep in mind that the shift lever has a **rotation point** in the middle. When you push the knob forward to engage first gear, you are actually pulling the rod and fork for first gear back.

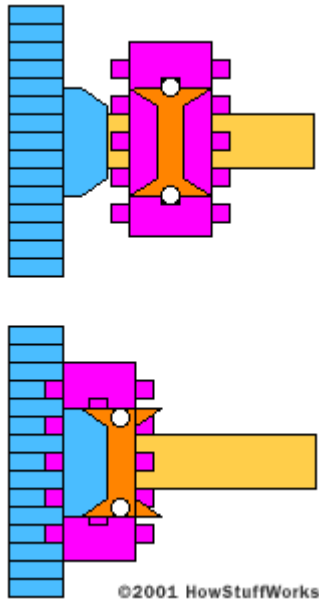
You can see that as you move the shifter **left and right** you are engaging different forks (and therefore different collars). Moving the knob **forward and backward** moves the collar to engage one of the gears.



Reverse gear is handled by a small idler gear (purple). Therefore, at all times, the blue reverse gear in this diagram is turning in a direction opposite to all of the other blue gears. It would be impossible to throw the transmission into reverse while the car is moving forward -- the dog teeth would never engage. They will make a lot of noise, however!

Synchronizers

Manual transmissions in modern passenger cars use **synchronizers** to eliminate the need for double-clutching. A synchro's purpose is to allow the collar and the gear to make frictional contact before the dog teeth make contact. This lets the collar and the gear synchronize their speeds before the teeth need to engage, like this:



The cone on the blue gear fits into the cone-shaped area in the collar, and friction between the cone and the collar synchronize the collar and the gear. The outer portion of the collar then slides so that the dog teeth can engage the gear.

Every manufacturer implements transmissions and synchros in different ways, but this is the general idea.

Clutch

If you drive a manual transmission car, you may be surprised to find out that your car has more than one clutch in it.

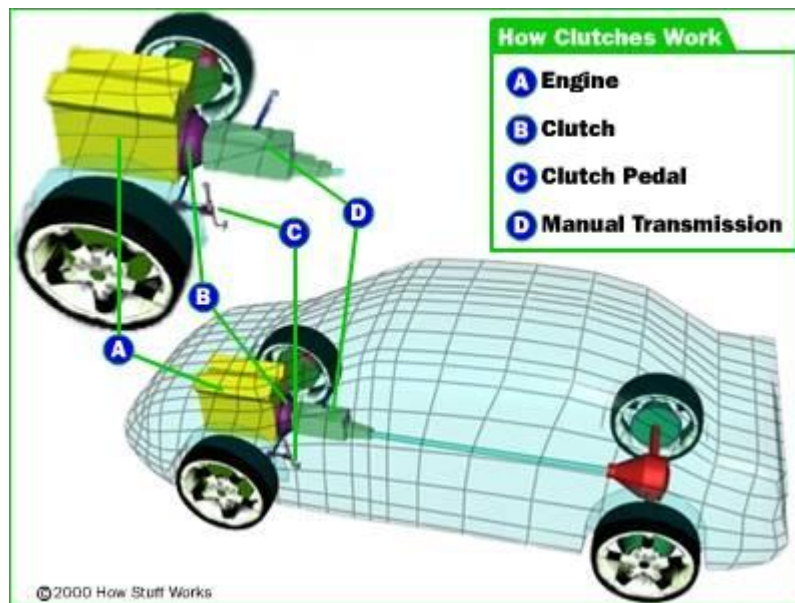


Figure 1. Diagram of car showing clutch location

Why Do We Need Clutches?

Clutches are useful in devices with two rotating shafts. In these devices, one of the shafts is typically driven by a motor or pulley, and the other shaft is driving another device. In a drill for instance, one shaft is driven by a motor, and the other is driving a drill chuck. The clutch connects the two shafts so that they can either be locked together and spin at the same speed, or they can be decoupled and spin at different speeds.

In a car, you need a clutch because the engine spins all the time, and the car wheels don't. In order for a car to stop without killing the engine, the wheels need to be disconnected from the engine somehow. The clutch allows us to smoothly engage a spinning engine to a non-spinning transmission, by controlling the slippage between them. To understand how a clutch works, it helps to know a little bit about [friction](#).

The flywheel is connected to the engine, and the clutch plate is connected to the transmission. When your foot is off the pedal, the springs push the pressure plate against the clutch disc, which in turn presses against the flywheel. This locks the engine to the transmission input shaft, causing them to spin at the same speed.



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Photo courtesy of Carolina Mustang

Figure 4. Pressure Plate

The amount of force the clutch can hold depends on the friction between the clutch plate and the flywheel, and how much force the spring puts on the pressure plate. When the clutch pedal is pressed, a cable or [hydraulic piston](#) pushes on the release fork, which presses the throw-out bearing against the middle of the diaphragm spring. As the middle of the diaphragm spring is pushed in, a series of pins near the outside of the spring cause the spring to pull the pressure plate away from the clutch disc (see **Figure 6**). This releases the clutch from the spinning engine.



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Photo courtesy of Carolina Mustang

Figure 6. Clutch Plate

Note the springs in the clutch plate. These springs help to isolate the transmission from the shock of the clutch engaging.

Automatic Transmission

There are two big differences between an automatic transmission and [manual transmission](#):

- There is no clutch pedal in an automatic transmission car
- There is no gear shift in an automatic transmission car. Once you put the transmission into Drive, everything else is automatic!

Both the automatic transmission (plus its [torque converter](#)) and a [manual transmission](#) (with its [clutch](#)) accomplish exactly the same thing, but they do it in totally different ways.

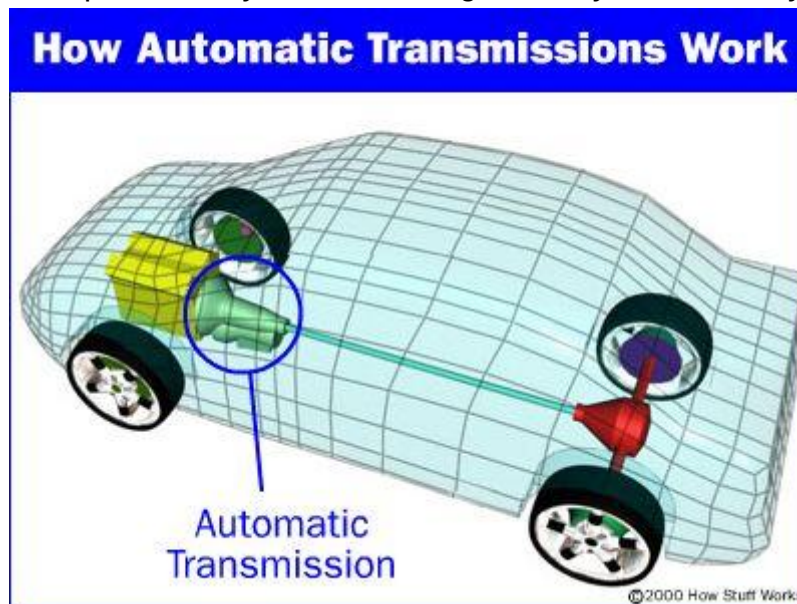


Figure
Location of the automatic transmission

1

Just like that of a manual transmission, the automatic transmission's primary job is to allow the engine to operate in its narrow range of speeds while providing a wide range of output speeds.

Without a transmission, cars would be limited to one [gear ratio](#), and that ratio would have to be selected to allow the car to travel at the desired top speed. If you wanted a top speed of 80 mph, then the gear ratio would be similar to third gear in most manual transmission cars.

You've probably never tried driving a manual transmission car using only third gear. If you did, you'd quickly find out that you had almost no acceleration when starting out, and, at high speeds, the engine would be screaming along near the red-line. A car like this would wear out very quickly and would be nearly undriveable.

So the transmission uses gears to make more effective use of the engine's [torque](#), and to keep the engine operating at an appropriate speed.

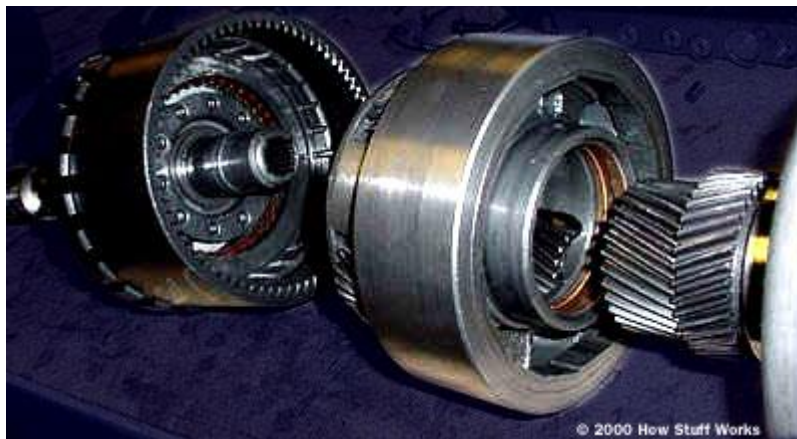
The key difference between a manual and an automatic transmission is that the manual transmission locks and unlocks different sets of [gears](#) to the output shaft to achieve the various gear ratios, while in an automatic transmission, the same set of gears produces all of the different gear ratios. The planetary gearset is the device that makes this possible in an automatic transmission...

Planetary Gearsets

When you take apart and look inside an automatic transmission, you find an amazing assortment of parts in a fairly small space. Among other things you see:

- An extremely ingenious planetary gearset
- A set of bands that lock parts of a gearset
- A set of 3 wet-plate clutches to lock other parts of the gearset
- An incredibly odd hydraulic control system that controls the clutches and bands
- A large gear pump to move transmission fluid around

The center of attention is the **planetary gearset**. About the size of a cantelope, this one part creates all of the different gear ratios that the transmission can produce. Everything else in the transmission is there to help the planetary gearset do its thing. This amazing piece of gearing has appeared on HowStuffWorks before. You may recognize it from the [electric screwdriver](#) article. An automatic transmission contains two complete planetary gearsets folded together into one component. See [How Gear Ratios Work](#) for an introduction to planetary gearsets.



From left to right: the ring gear, planet carrier, and two sun gears.

Any planetary gearset has three main components:

- the **sun gear**
- the **planet gears** and the planet gears' **carrier**
- the **ring gear**.

Each of these three components can be the input, the output or can be held stationary. Choosing which piece plays which role determines the gear ratio for the gearset. Let's take a look at a single planetary gearset.

One of the planetary gearsets from our transmission has a ring gear with 72 teeth and a sun gear with 30 teeth. We can get lots of different gear ratios out of this gearset.

	Input	Output	Stationary	Calculation	Gear Ratio
A	Sun (S)	Planet Carrier (C)	Ring (R)	$1 + R/S$	3.4:1
B	Planet Carrier (C)	Ring (R)	Sun (S)	$1 / (1 + S/R)$	0.71:1
C	Sun (S)	Ring (R)	Planet Carrier (C)	$-R/S$	-2.4:1

Also, locking any two of the three components together will lock up the whole device at a 1:1 gear reduction. Notice that the first gear ratio listed above is a reduction -- the output speed is slower than the input speed. The second is an overdrive -- the output speed is faster than the input speed. The last is a reduction again, but the output direction is reversed. There are several other ratios that can be gotten out of this planetary gear set, but these are the ones that are relevant to our automatic transmission. You can try these out in the animation below:

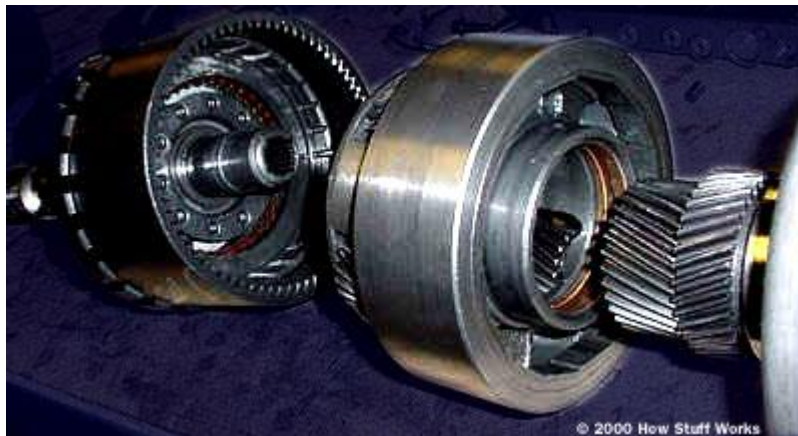
So this one set of gears can produce all of these different gear ratios without having to engage or disengage any other gears. With two of these gearsets in a row, we can get the four forward gears and one reverse gear our transmission needs. We'll put the two sets of gears together in the next section.

Gears

This automatic transmission uses a set of gears, called a **compound planetary gearset**, that looks like a single planetary gearset but actually behaves like two planetary gearsets combined. It has one ring gear that is always the output of the transmission, but it has two sun gears and two sets of planets.

Let's look at some of the parts.

Figure 3 shows how the gears in the transmission are put together.



Figure

From left to right: the ring gear, planet carrier, and two sun gears.

Figure 4 shows the planets in the planet carrier. Notice how the planet on the right sits lower than the planet on the left. The planet on the right does not engage the ring gear -- it engages the other planet. Only the planet on the left engages the ring gear.



Figure 4
Planet carrier: Note the two sets of planets.

Figure 5 shows the inside of the planet carrier. The shorter gears are engaged only by the smaller sun gear. The longer planets are engaged by the bigger sun gear and by the smaller planets.

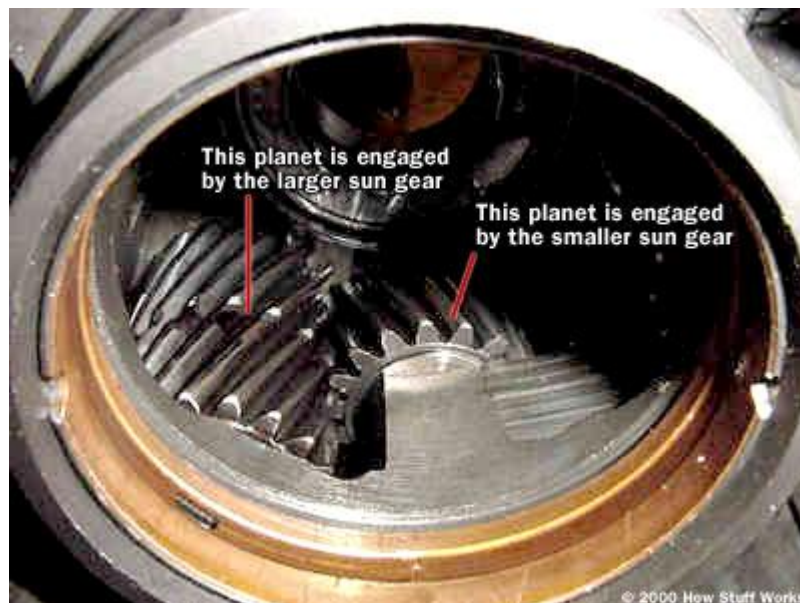


Figure 5
Inside of the planet carrier: Note the two sets of planets.

First Gear

In first gear, the smaller sun gear is driven clockwise by the turbine in the [torque converter](#). The planet carrier tries to spin counterclockwise, but is held still by the one-way [clutch](#) (which only allows rotation in the clockwise direction) and the ring gear turns the output. The small gear has 30 teeth and the ring gear has 72, so referring to the chart on the previous page, the gear ratio is:

$$\text{Ratio} = -R/S = -72/30 = -2.4:1$$

So the rotation is negative 2.4:1, which means that the output direction would be **opposite** the input direction. But the output direction is really the **same** as the input direction -- this is where the trick with the two sets of planets comes in. The first set of planets engages the second set, and the second set turns the ring gear; this combination reverses the direction. You can see that this would also cause the bigger sun gear to spin; but because that clutch is released, the bigger sun gear is free to spin in the opposite direction of the turbine (counterclockwise).

Second Gear

This transmission does something really neat in order to get the ratio needed for second gear. It acts like two planetary gearsets connected to each other with a common planet carrier.

The first stage of the planet carrier actually uses the larger sun gear as the ring gear. So the first stage consists of the sun (the smaller sun gear), the planet carrier, and the ring (the larger sun gear).

The input is the small sun gear; the ring gear (large sun gear) is held stationary by the band, and the output is the planet carrier. For this stage, with the sun as input, planet carrier as output, and the ring gear fixed, the formula is:

$$1 + R/S = 1 + 36/30 = 2.2:1$$

The planet carrier turns 2.2 times for each rotation of the sun gear. At the second stage, the planet carrier acts as the input for the second planetary gear set, the larger sun gear (which is held stationary) acts as the sun, and the ring gear acts as the output, so the gear ratio is:

$$1 / (1 + S/R) = 1 / (1 + 36/72) = 0.67:1$$

To get the overall reduction for second gear, we multiply the first stage by the second, 2.2 x 0.67, to get a 1.47:1 reduction. This may sound wacky, but it works.

Third Gear

Most automatic transmissions have a 1:1 ratio in third gear. You'll remember from the previous section that all we have to do to get a 1:1 output is lock together any two of the three parts of the planetary gear. With the arrangement in this gearset it is even easier -- all we have to do is engage the clutches that lock each of the sun gears to the turbine.

If both sun gears turn in the same direction, the planet gears lockup because they can only spin in opposite directions. This locks the ring gear to the planets and causes everything to spin as a unit, producing a 1:1 ratio.

Overdrive

By definition, an overdrive has a faster output speed than input speed. It's a speed increase -- the opposite of a reduction. In this transmission, engaging the overdrive accomplishes two things at once. If you read [How Torque Converters Work](#), you learned about lockup torque converters. In order to improve efficiency, some cars have a mechanism that locks up the torque converter so that the output of the engine goes straight to the transmission.

In this transmission, when overdrive is engaged, a shaft that is attached to the housing of the torque converter (which is bolted to the flywheel of the engine) is connected by clutch to the planet carrier. The small sun gear freewheels, and the larger sun gear is held by the overdrive band. Nothing is connected to the turbine; the only input comes from the converter housing. Let's go back to our chart again, this time with the planet carrier for input, the sun gear fixed and the ring gear for output.

$$\text{Ratio} = 1 / (1 + S/R) = 1 / (1 + 36/72) = 0.67:1$$

So the output spins once for every two-thirds of a rotation of the engine. If the engine is turning at 2000 rotations per minute (RPM), the output speed is 3000 RPM. This allows cars to drive at freeway speed while the engine speed stays nice and slow.

Reverse

Reverse is very similar to first gear, except that instead of the small sun gear being driven by the torque converter turbine, the bigger sun gear is driven, and the small one freewheels in the opposite direction. The planet carrier is held by the reverse band to the housing. So, according to our equations from the last page, we have:

Ratio = $-R/S = 72/36 = 2.0:1$

So the ratio in reverse is a little less than first gear in this transmission.

Gear Ratios

This transmission has four forward gears and one reverse gear. Let's summarize the gear ratios, inputs and outputs:

Gear	Input	Output	Fixed	Gear Ratio
1st	30 tooth sun	72 tooth ring	Planet Carrier	2.4:1
2nd	30 tooth sun	Planet Carrier	36 tooth ring	2.2:1
	Planet Carrier	72 tooth ring	36 tooth sun	0.67:1
			Total 2nd gear	1.47:1
3rd	30 and 36 tooth suns	72 tooth ring		1.0:1
OD	Planet Carrier	72 tooth ring	36 tooth sun	0.67:1
Reverse	36 tooth sun	72 tooth ring	Planet Carrier	-2.0:1

After reading this section, you are probably wondering how the different inputs get connected and disconnected. This is done by a series of clutches and bands inside the transmission. In the next section, we'll see how these work.

The Clutches and Bands

In the last section, we discussed how each of the gear ratios is created by the transmission. For instance, when we discussed overdrive, we said:

In this transmission, when overdrive is engaged, a shaft that is attached to the housing of the torque converter (which is bolted to the flywheel of the engine) is connected by clutch to the planet carrier. The small sun gear freewheels, and the larger sun gear is held by the overdrive band. Nothing is connected to the turbine; the only input comes from the converter housing.

To get the transmission into overdrive, lots of things have to be connected and disconnected by clutches and bands. The planet carrier gets connected to the torque converter housing by a clutch. The small sun gets disconnected from the turbine by a clutch so that it can freewheel. The big sun gear is held to the housing by a band so that it could not rotate. Each gear shift triggers a series of events like these, with different clutches and bands engaging and disengaging. Let's take a look at a band.

Bands

In this transmission there are two bands. The bands in a transmission are, literally, steel bands that wrap around sections of the gear train and connect to the housing. They are actuated by hydraulic cylinders inside the case of the transmission.



Figure
One of the bands

7

In **Figure 7** you can see one of the bands in the housing of the transmission. The geartrain is removed. The metal rod is connected to the piston, which actuates the band.

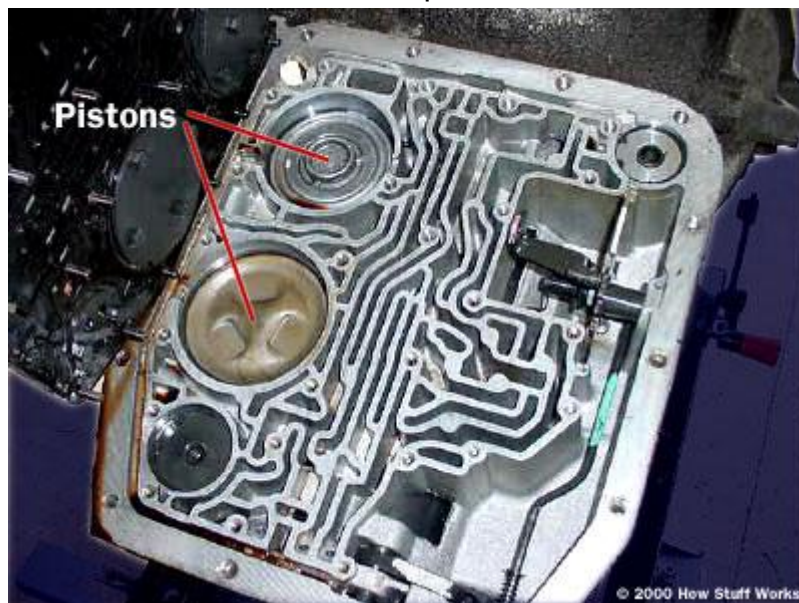


Figure
The pistons that actuate the bands are visible above.

8

In **Figure 8** you can see the two pistons that actuate the bands. Hydraulic pressure, routed into the cylinder by a set of valves, causes the pistons to push on the bands, locking that part of the gear train to the housing.

Clutches

The [clutches](#) in the transmission are a little more complex. In this transmission there are four clutches. Each clutch is actuated by pressurized hydraulic fluid that enters a piston inside the clutch. Springs make sure that the clutch releases when the pressure is

reduced. **Figure 9** shows the piston and the clutch drum. Notice the rubber seal on the piston -- this is one of the components that is replaced when your transmission gets rebuilt.

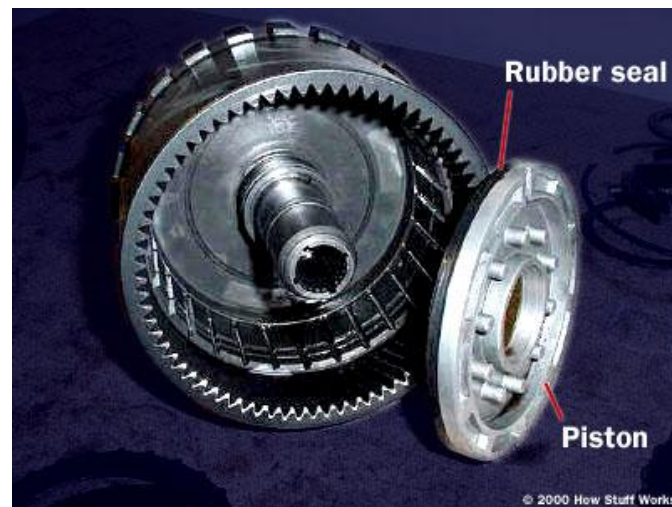


Figure 9
One of the clutches in a transmission 9

Figure 10 shows the alternating layers of clutch friction material and steel plates. The friction material is splined on the inside, where it locks to one of the gears. The steel plate is splined on the outside, where it locks to the clutch housing. These clutch plates are also replaced when the transmission is rebuilt.



Figure 10
The clutch plates 10

The pressure for the clutches is fed through passageways in the shafts. The hydraulic system controls which clutches and bands are energized at any given moment.

When You Put the Car in Park

It may seem like a simple thing to lock the transmission and keep it from spinning; but there are actually some complex requirements for this mechanism:

- You have to be able to disengage it when the car is on a hill (the weight of the car is resting on the mechanism).
- You have to be able to engage the mechanism even if the lever does not line up with the gear.
- Once engaged, something has to prevent the lever from popping up and disengaging.

The mechanism that does all this is pretty neat. Let's look at some of the parts first.



Figure 11
The output of the transmission
The square notches are engaged by the parking-brake mechanism to hold the car still.

Figure 11 shows the output section of the transmission. The parking-brake mechanism engages the teeth on the output to hold the car still. This is the section of the transmission that hooks up to the driveshaft -- so if this part can't spin, the car can't move.



Figure 12
The empty housing of the transmission with the parking brake mechanism poking through, as it does when the car is in park

Figure 12 shows the park mechanism protruding into the housing where the gears are located. Notice that it has tapered sides. This helps to disengage the parking brake when you are parked on a hill -- the force from the weight of the car helps to push the parking mechanism out of place because of the angle of the taper.

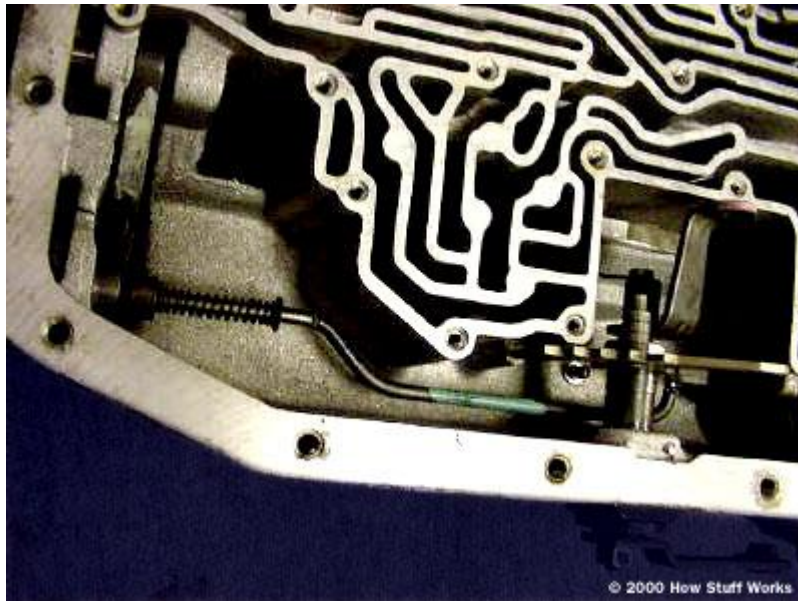


Figure 13
This rod actuates the park mechanism.

Figure 13 shows the rod that actuates the park mechanism. This rod is connected to a cable that is operated by the shift lever in your car.

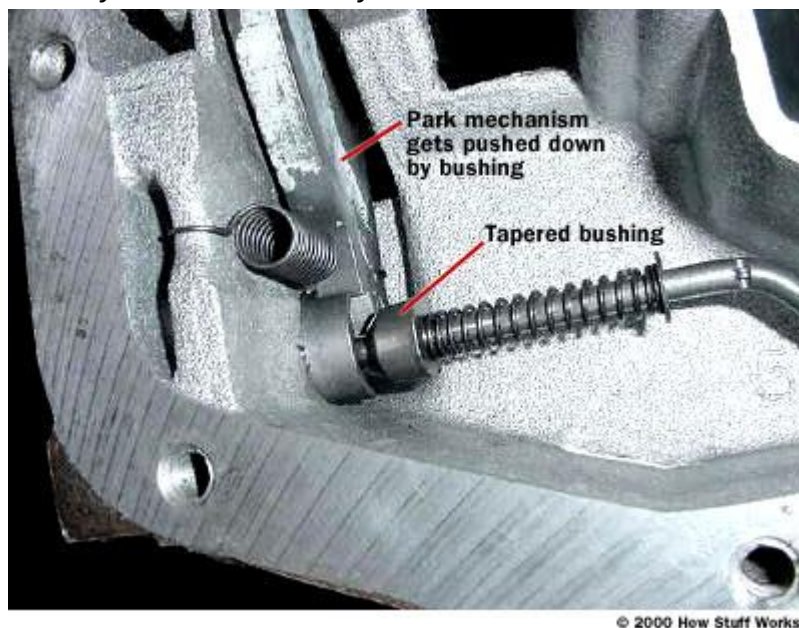


Figure 14
The park mechanism

Figure 14 shows the park mechanism from the top. When the shift lever is placed in park, the rod pushes the spring against the small tapered bushing. If the park mechanism is lined up so that it can drop into one of the notches in the output gear section, the tapered bushing will push the mechanism down. If the mechanism is lined up on one of the high spots on the output, then the spring will push on the tapered bushing, but the lever will not lock into place until the car rolls a little and the teeth line up properly. This is why sometimes your car moves a little bit after you put it in park and release the brake pedal -- it has to roll a little for the teeth to line up to where the parking mechanism can drop into place.

Once the car is safely in park, the bushing holds down the lever so that the car will not pop out of park if it is on a hill.

The Hydraulic System

The automatic transmission in your car has to do numerous tasks. You may not realize how many different ways it operates. For instance, here are some of the features of an automatic transmission:

- If the car is in overdrive (on a four-speed transmission), the transmission will automatically select the gear based on vehicle speed and throttle pedal position.
- If you accelerate gently, shifts will occur at lower speeds than if you accelerate at full throttle.
- If you floor the gas pedal, the transmission will downshift to the next lower gear.
- If you move the shift selector to a lower gear, the transmission will downshift unless the car is going too fast for that gear. If the car is going too fast, it will wait until the car slows down and then downshift.
- If you put the transmission in second gear, it will never downshift or upshift out of second, even from a complete stop, unless you move the shift lever.

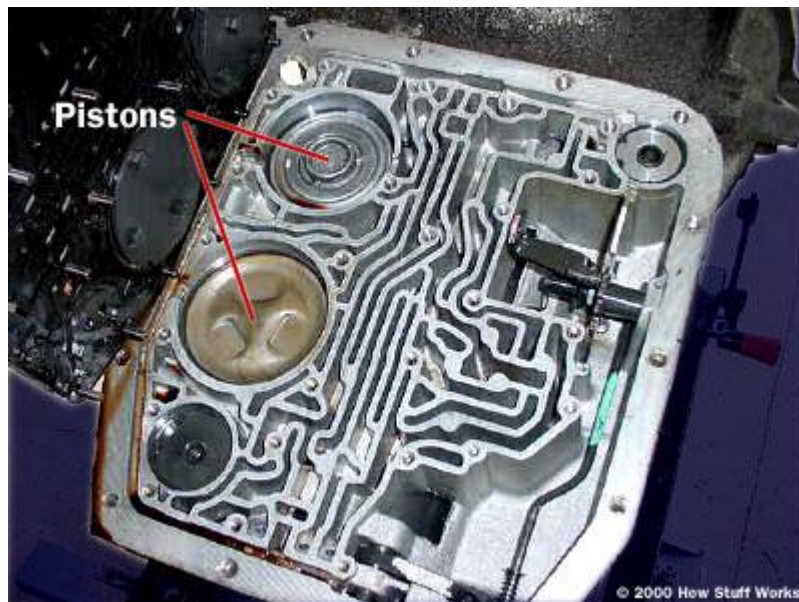


Figure 15

You've probably seen something that looks like **Figure 15** before. It is really the brain of the automatic transmission, managing all of these functions and more. The passageways you can see route fluid to all the different components in the transmission. Passageways molded into the metal are an efficient way to route fluid; without them, many hoses would be needed to connect the various parts of the transmission. First, we'll discuss the key components of the hydraulic system; then we'll see how they work together.

The Pump

Automatic transmissions have a neat pump, called a **gear pump**. The pump is usually located in the cover of the transmission. It draws fluid from a sump in the bottom of the transmission and feeds it to the hydraulic system. It also feeds the [transmission cooler](#) and the [torque converter](#).



Figure 16
Gear pump from an automatic transmission

The inner gear of the pump hooks up to the housing of the torque converter, so it spins at the same speed as the engine. The outer gear is turned by the inner gear, and as the gears rotate, fluid is drawn up from the sump on one side of the crescent and forced out into the hydraulic system on the other side.

The Governor

The **governor** is a clever valve that tells the transmission how fast the car is going. It is connected to the output, so the faster the car moves, the faster the governor spins. Inside the governor is a springloaded valve that opens in proportion to how fast the governor is spinning -- the faster the governor spins, the more the valve opens. Fluid from the pump is fed to the governor through the output shaft.

The faster the car goes, the more the governor valve opens and the higher the pressure of the fluid it lets through.

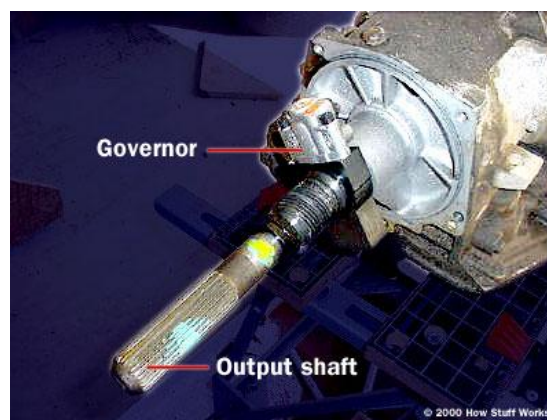


Figure 17 The governor

Throttle Valve or Modulator

To shift properly, the automatic transmission has to know how hard the engine is working. There are two different ways that this is done. Some cars have a simple cable linkage connected to a **throttle valve** in the transmission. The further the gas pedal is pressed, the more pressure is put on the throttle valve. Other cars use a **vacuum modulator** to apply pressure to the throttle valve. The modulator senses the manifold pressure, which drops when the engine is under a greater load.

Manual Valve

The **manual valve** is what the shift lever hooks up to. Depending on which gear is selected, the manual valve feeds hydraulic circuits that inhibit certain gears. For instance, if the shift lever is in third gear, it feeds a circuit that prevents overdrive from engaging.

Shift Valves

Shift valves supply hydraulic pressure to the clutches and bands to engage each gear. The valve body of the transmission contains several shift valves. The shift valve determines when to shift from one gear to the next. For instance, the 1 to 2 shift valve determines when to shift from first to second gear. The shift valve is pressurized with fluid from the governor on one side, and the throttle valve on the other. They are supplied with fluid by the pump, and they route that fluid to one of two circuits to control which gear the car runs in.

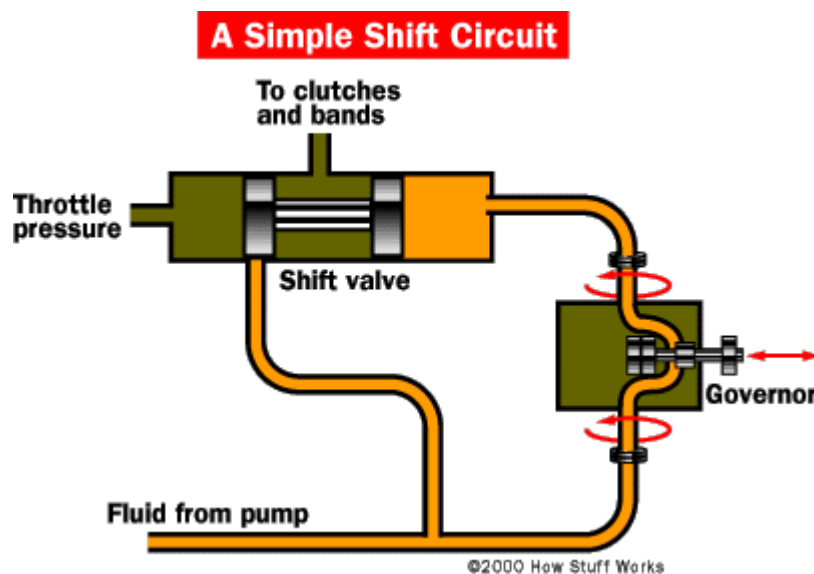


Figure
The shift circuit

18

The shift valve will delay a shift if the car is accelerating quickly. If the car accelerates gently, the shift will occur at a lower speed. Let's discuss what happens when the car accelerates gently.

As car speed increases, the pressure from the governor builds. This forces the shift valve over until the first gear circuit is closed, and the second gear circuit opens. Since the car is accelerating at light throttle, the throttle valve does not apply much pressure against the shift valve.

When the car accelerates quickly, the throttle valve applies more pressure against the shift valve. This means that the pressure from the governor has to be higher (and therefore the vehicle speed has to be faster) before the shift valve moves over far enough to engage second gear.

Each shift valve responds to a particular pressure range; so when the car is going faster, the 2 to 3 shift valve will take over, because the pressure from the governor is high enough to trigger that valve.

Electronic Controls

Electronically controlled transmissions, which appear on some newer cars, still use hydraulics to actuate the clutches and bands, but each hydraulic circuit is controlled by an electric solenoid. This simplifies the plumbing on the transmission and allows for more advanced control schemes.

In the last section we saw some of the control strategies that mechanically controlled transmissions use. Electronically controlled transmissions have even more elaborate control schemes. In addition to monitoring vehicle speed and throttle position, the transmission controller can monitor the engine speed, if the brake pedal is being pressed, and even the [anti-lock braking system](#).

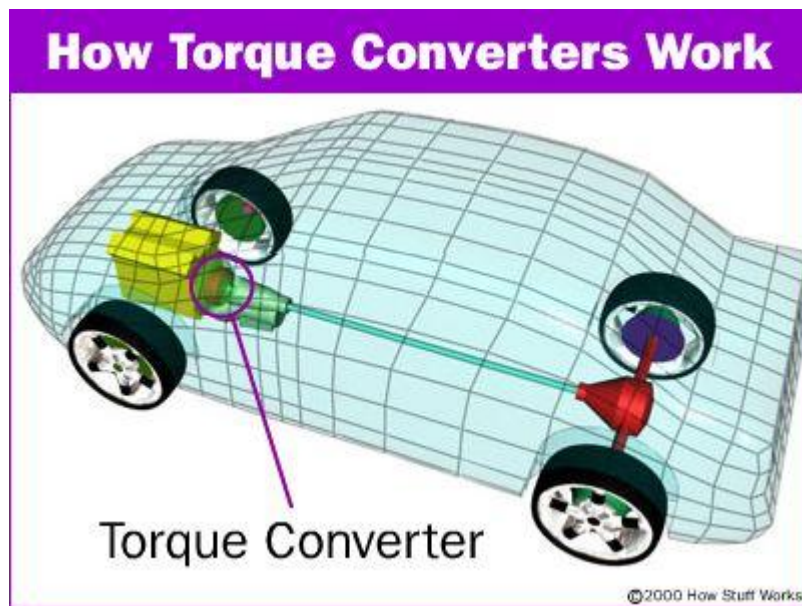
Using this information and an advanced control strategy based on fuzzy logic -- a method of programming control systems using human-type reasoning -- electronically controlled transmissions can do things like:

- Downshift automatically when going downhill, to control speed and reduce wear on the brakes.
- Upshift when braking on a slippery surface to reduce the braking torque applied by the engine.
- Inhibit the upshift when going into a turn on a winding road.

Inhibiting the upshift when going into a turn on a winding road. Let's say you're driving on an uphill, winding mountain road. When you are driving on the straight sections of the road, the transmission shifts into second gear to give you enough acceleration and hill-climbing power. When you come to a curve you slow down, taking your foot off the gas pedal and possibly applying the brake. Most transmissions will upshift to third gear, or even overdrive, when you take your foot off the gas. Then when you accelerate out of the curve, they will downshift again. But if you were driving a manual transmission car, you would probably leave the car in the same gear the whole time. Some automatic transmissions with advanced control systems can detect this situation after you have gone around a couple of the curves, and "learn" not to upshift again.

Torque Converter

Cars with an automatic transmission have no [clutch](#) that disconnects the transmission from the engine. Instead, they use an amazing device called a **torque converter**. It may not look like much, but there are some very interesting things going on inside. Just like manual transmission cars, cars with automatic transmissions need a way to let the engine turn while the wheels and [gears](#) in the transmission come to a stop. Manual transmission cars use a [clutch](#), which completely disconnects the engine from the transmission. Automatic transmission cars use a torque converter.



The torque converter is situated between the engine and the transmission.

If the engine is turning slowly, such as when the car is idling at a stoplight, the amount of [torque](#) passed through the torque converter is very small, so keeping the car still requires only a light pressure on the [brake](#) pedal.

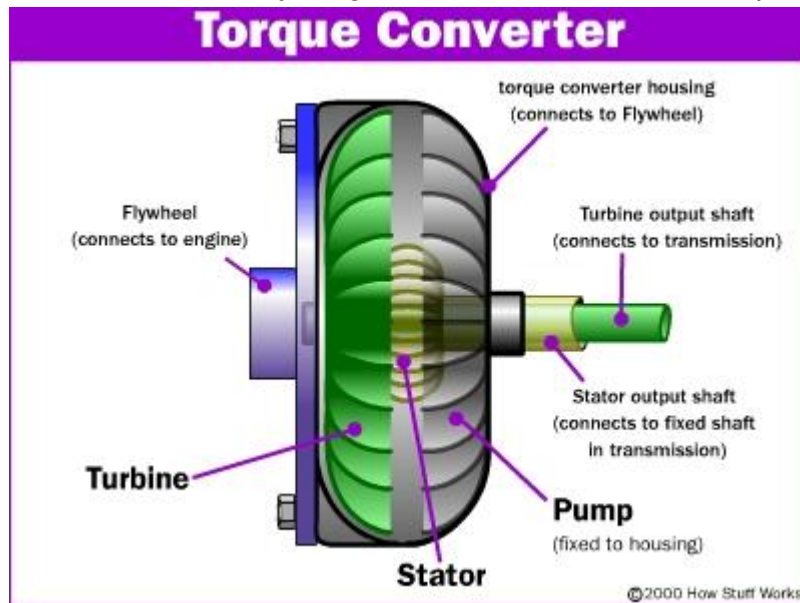
If you were to step on the gas pedal while the car is stopped, you would have to press harder on the brake to keep the car from moving. This is because when you step on the gas, the engine speeds up and pumps more fluid into the torque converter, causing more torque to be transmitted to the wheels. As shown in the figure below, there are four components inside the very strong housing of the torque converter:

- **Pump**
- **Turbine**
- **Stator**
- **Transmission fluid**



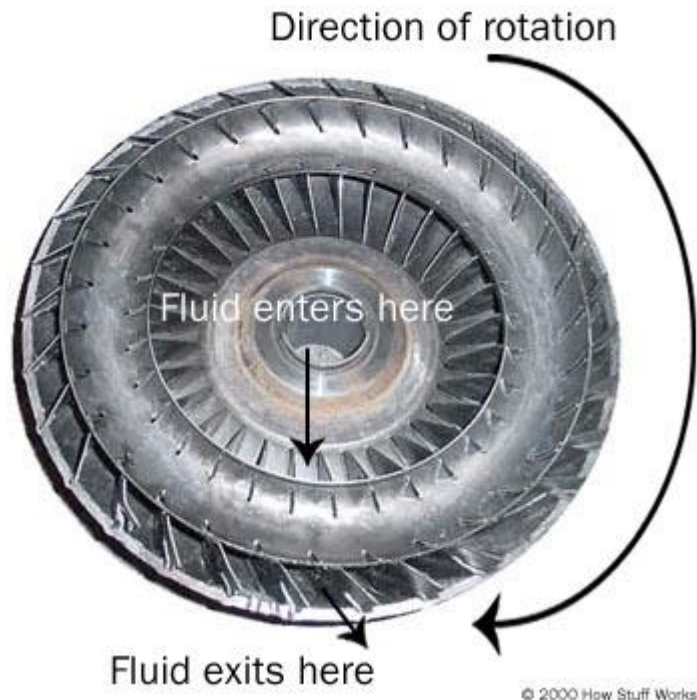
The parts of a torque converter (left to right): turbine, stator and pump

The **housing** of the torque converter is bolted to the flywheel of the engine, so it turns at whatever speed the engine is running at. The **fins** that make up the pump of the torque converter are attached to the housing, so they also turn at the same speed as the engine. The cutaway below shows how everything is connected inside the torque converter.



How the parts of the torque converter connect to the transmission and engine

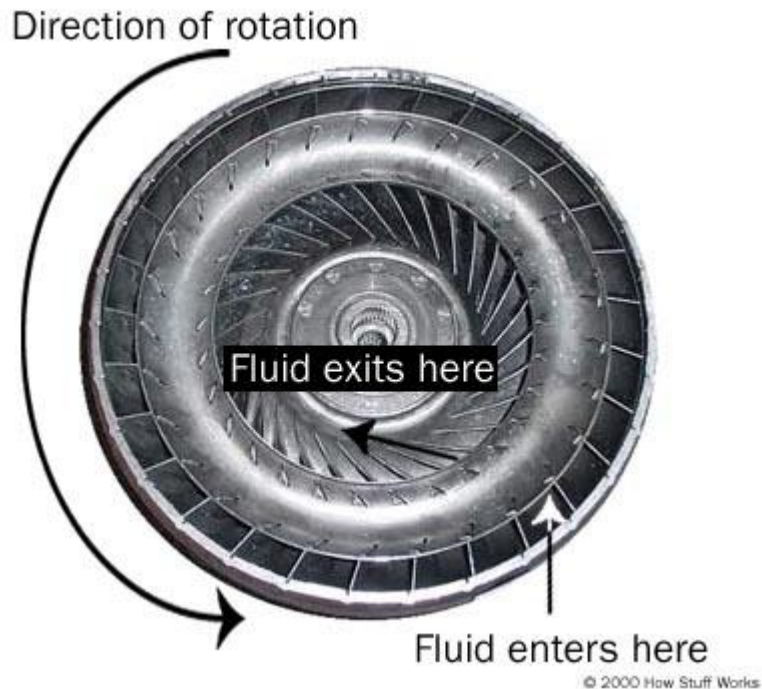
The **pump** inside a torque converter is a type of centrifugal pump. As it spins, fluid is flung to the outside, much as the spin cycle of a [washing machine](#) flings water and clothes to the outside of the wash tub. As fluid is flung to the outside, a vacuum is created that draws more fluid in at the center.



The pump section of the torque converter is attached to the housing.

The fluid then enters the blades of the **turbine**, which is connected to the transmission. The turbine causes the transmission to spin, which basically moves your car. You can see

in the graphic below that the blades of the turbine are curved. This means that the fluid, which enters the turbine from the outside, has to change direction before it exits the center of the turbine. It is this **directional change** that causes the turbine to spin.



The torque converter turbine: Note the spline in the middle. This is where it connects to the transmission.

In order to change the direction of a moving object, you must apply a [force](#) to that object -- it doesn't matter if the object is a car or a drop of fluid. And whatever applies the force that causes the object to turn must also feel that force, but in the opposite direction. So as the turbine causes the fluid to change direction, the fluid causes the turbine to spin.

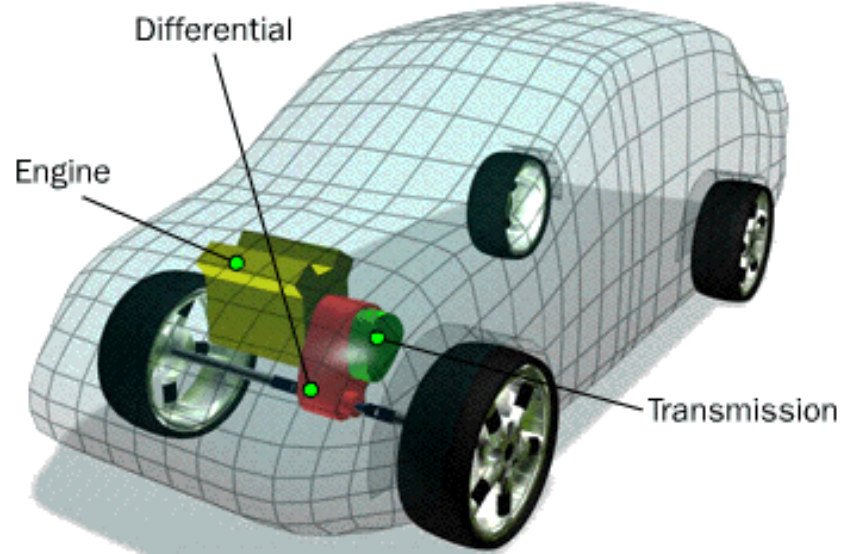
The fluid exits the turbine at the center, moving in a different direction than it was when it entered. If you look at the arrows in the figure above, you can see that the fluid exits the turbine moving opposite the direction that the pump (and engine) are turning. If the fluid were allowed to hit the pump, it would slow the engine down, wasting power. This is why a torque converter has a **stator**.

Differential

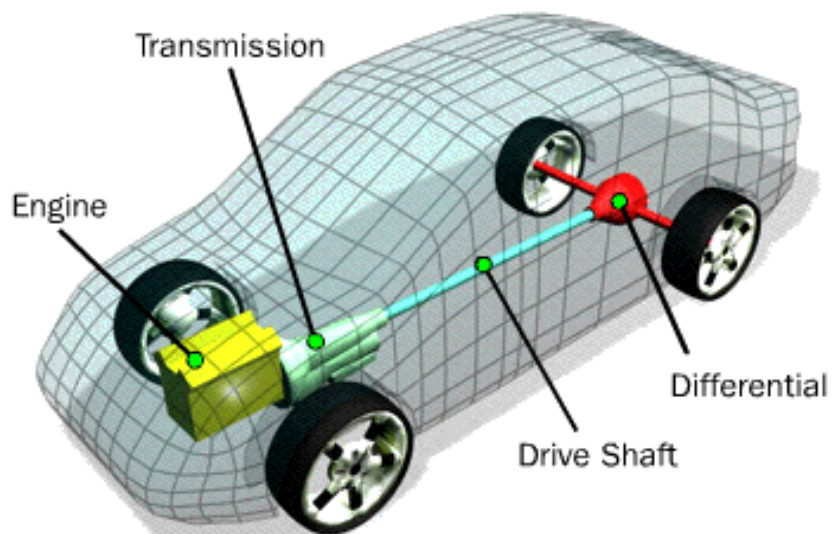
The differential has three jobs:

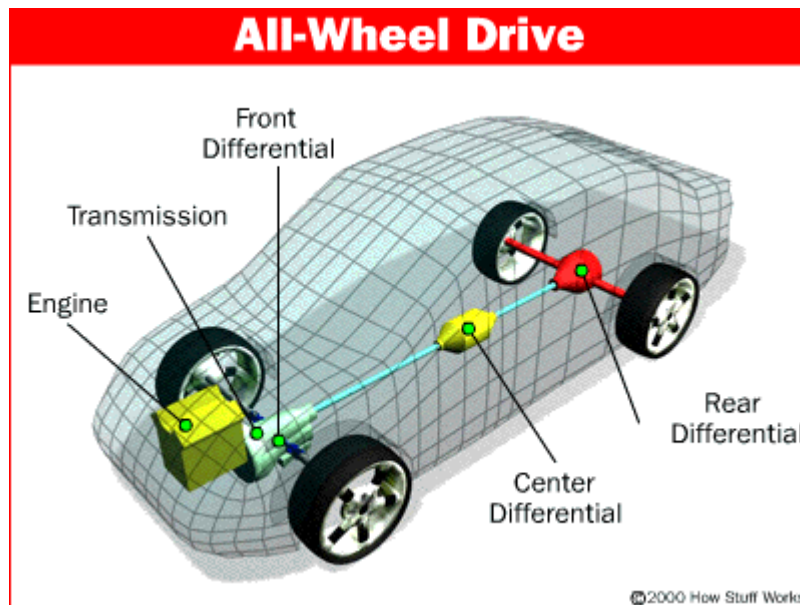
- To aim the engine power at the wheels
- To act as the final [gear reduction](#) in the vehicle, slowing the rotational speed of the transmission one final time before it hits the wheels
- To transmit the power to the wheels while allowing them to rotate at different speeds (This is the one that earned the differential its name.)

Front-Wheel Drive



Rear-Wheel Drive





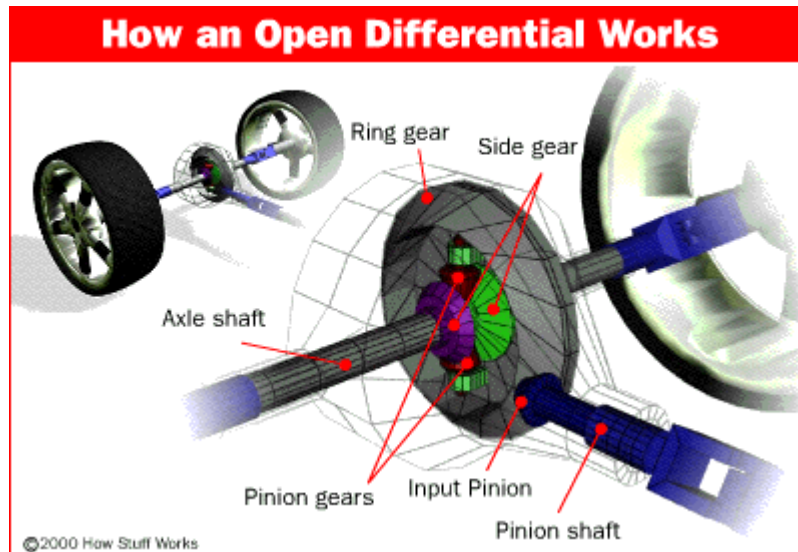
Car wheels spin at different speeds, especially when turning. You can see from the animation below that each wheel travels a different distance through the turn, and that the inside wheels travel a shorter distance than the outside wheels. Since speed is equal to the distance traveled divided by the time it takes to go that distance, the wheels that travel a shorter distance travel at a lower speed. Also note that the front wheels travel a different distance than the rear wheels.

For the **non-driven wheels** on your car -- the front wheels on a rear-wheel drive car, the back wheels on a front-wheel drive car -- this is not an issue. There is no connection between them, so they spin independently. But the driven wheels are linked together so that a single engine and transmission can turn both wheels. If your car did not have a differential, the wheels would have to be locked together, forced to spin at the same speed. This would make turning difficult and hard on your car: For the car to be able to turn, one [tire](#) would have to slip. With modern tires and concrete roads, a great deal of force is required to make a tire slip. That force would have to be transmitted through the axle from one wheel to another, putting a heavy strain on the axle components.

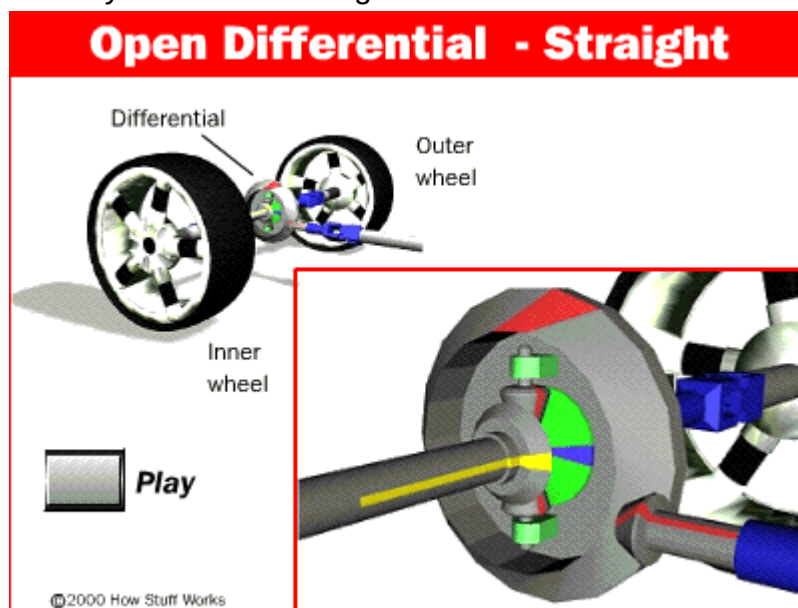
The differential is a device that splits the engine [torque](#) two ways, allowing each output to spin at a different speed. It is found on all modern cars and trucks, and also in many all-wheel-drive (full-time [four-wheel-drive](#)) vehicles. These all-wheel-drive vehicles need a differential between each set of drive wheels, and they need one between the front and the back wheels as well, because the front wheels travel a different distance through a turn than the rear wheels.

Part-time four-wheel-drive systems don't have a differential between the front and rear wheels; instead, they are locked together so that the front and rear wheels have to turn at the same average speed. This is why these vehicles are hard to turn on concrete when the four-wheel-drive system is engaged.

Open Differential



Let's start by looking at what happens when a car is driving straight down the road (see image below), and both drive wheels are spinning at the same speed. The **input pinion** is turning the ring gear and cage, and none of the pinions within the cage are rotating -- both side gears are effectively locked to the cage.



Also note that the input pinion is a smaller gear than the ring gear; this is the last gear reduction in the car. You may have heard terms like **rear axle ratio** or **final drive ratio**. These refer to the gear ratio in the differential. If the final drive ratio is 4.10, then the ring gear has 4.10 times as many teeth as the input pinion gear when a car makes a turn, the wheels must spin at different speeds. In the figure below, you can see that the pinions in the cage start to spin as the car begins to turn, allowing the wheels to move at different speeds. The inside wheel spins slower than the cage, while the outside wheel spins faster. The open differential always applies the same amount of [torque](#) to each wheel. There are two factors that determine how much torque can be applied to the wheels: equipment and traction. In dry conditions, when there is plenty of traction, the amount of torque applied to

the wheels is limited by the engine and gearing; in a low traction situation, such as when driving on ice, the amount of torque is limited to the greatest amount that will not cause a wheel to slip under those conditions. So, even though a car may be able to produce more torque, there needs to be enough traction to transmit that torque to the ground. If you give the car more gas after the wheels start to slip, the wheels will just spin faster.

If you've ever driven on ice, you may know of a trick that makes acceleration easier: If you start out in second gear, or even third gear, instead of first, because of the gearing in the [transmission](#) you will have less torque available to the wheels. This will make it easier to accelerate without spinning the wheels.

Now what happens if one of the drive wheels has good traction, and the other one is on ice? This is where the problem with open differentials comes in.

Remember that the open differential always applies the same torque to both wheels, and the maximum amount of torque is limited to the greatest amount that will not make the wheels slip. It doesn't take much torque to make a tire slip on ice. And when the wheel with good traction is only getting the very small amount of torque that can be applied to the wheel with less traction, your car isn't going to move very much.

Another time open differentials might get you into trouble is when you are driving off-road. If you have a four-wheel drive truck, or an SUV, with an open differential on both the front and the back, you could get stuck. If one of the front tires and one of the back tires comes off the ground, they will just spin helplessly in the air, and you won't be able to move at all.

The solution to these problems is the **limited slip differential** (LSD), sometimes called **positraction**. Limited slip differentials use various mechanisms to allow normal differential action when going around turns. When a wheel slips, they allow more torque to be transferred to the non-slipping wheel.

The next few sections will detail some of the different types of limited slip differentials, including the clutch-type LSD, the viscous coupling, locking differential and Torsen differential.

Clutch-Type Limited Slip

The clutch-type LSD is probably the most common version of the limited slip differential.



Image courtesy [Eaton Automotive Group's](#) Torque Control Products Division

This type of LSD has all of the same components as an open differential, but it adds a **spring pack** and a set of **clutches**. Some of these have a cone clutch that is just like the synchronizers in a [manual transmission](#).

The spring pack pushes the side gears against the [clutches](#), which are attached to the cage. Both side gears spin with the cage when both wheels are moving at the same speed, and the clutches aren't really needed -- the only time the clutches step in is when something happens to make one wheel spin faster than the other, as in a turn. The clutches fight this behaviour, wanting both wheels to go the same speed. If one wheel wants to spin faster than the other, it must first overpower the clutch. The stiffness of the springs combined with the friction of the clutch determine how much torque it takes to overpower it.

Getting back to the situation in which one drive wheel is on the ice and the other one has good traction: With this limited slip differential, even though the wheel on the ice is not able to transmit much torque to the ground, the other wheel will still get the torque it needs to move. The torque supplied to the wheel not on the ice is equal to the amount of torque it takes to overpower the clutches. The result is that you can move forward, although still not with the full power of your car.

Viscous Coupling

The **viscous coupling** is often found in all-wheel-drive vehicles. It is commonly used to link the back wheels to the front wheels so that when one set of wheels starts to slip, torque will be transferred to the other set.

The viscous coupling has two sets of plates inside a sealed housing that is filled with a thick fluid, as shown in below. One set of plates is connected to each output shaft. Under normal conditions, both sets of plates and the viscous fluid spin at the same speed. When one set of wheels tries to spin faster, perhaps because it is slipping, the set of plates corresponding to those wheels spins faster than the other. The viscous fluid, stuck between the plates, tries to catch up with the faster disks, dragging the slower disks along. This transfers more torque to the slower moving wheels -- the wheels that are not slipping. When a car is turning, the difference in speed between the wheels is not as large as when one wheel is slipping. The faster the plates are spinning relative to each other, the more torque the viscous coupling transfers. The coupling does not interfere with turns because the amount of torque transferred during a turn is so small. However, this also highlights a disadvantage of the viscous coupling: No torque transfer will occur until a wheel actually starts slipping.

A simple experiment with an egg will help explain the behavior of the viscous coupling. If you set an egg on the kitchen table, the shell and the yolk are both stationary. If you suddenly spin the egg, the shell will be moving at a faster speed than the yolk for a second, but the yolk will quickly catch up. To prove that the yolk is spinning, once you have the egg spinning quickly stop it and then let go -- the egg will start to spin again (unless it is hard boiled). In this experiment, we used the friction between the shell and the yolk to apply force to the yolk, speeding it up. When we stopped the shell, that friction -- between the still-moving yolk and the shell -- applied force to the shell, causing it to speed up. In a viscous coupling, the force is applied between the fluid and the sets of plates in the same way as between the yolk and the shell.

Locking and Torsen®

The **locking differential** is useful for serious off-road vehicles. This type of differential has the same parts as an open differential, but adds an electric, pneumatic or hydraulic mechanism to lock the two output pinions together.

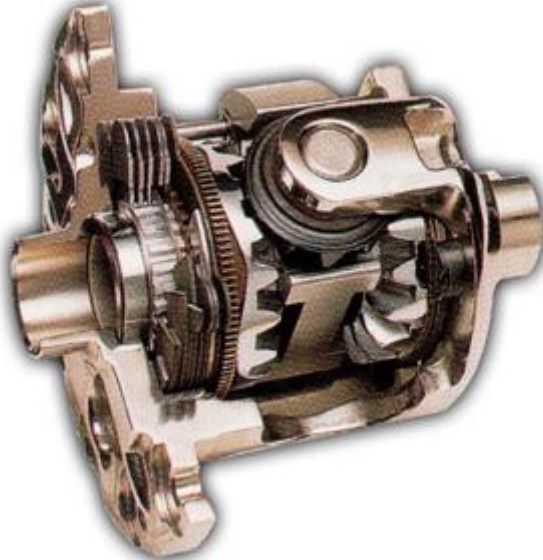


Image courtesy [Eaton Automotive Group's](#) Torque Control Products Division

This mechanism is usually activated manually by switch, and when activated, both wheels will spin at the same speed. If one wheel ends up off the ground, the other wheel won't know or care. Both wheels will continue to spin at the same speed as if nothing had changed.

The **Torsen differential*** is a purely mechanical device; it has no electronics, clutches or viscous fluids.

The Torsen (from **Torque Sensing**) works as an open differential when the amount of torque going to each wheel is equal. As soon as one wheel starts to lose traction, the difference in torque causes the gears in the Torsen differential to bind together. The design of the gears in the differential determines the **torque bias ratio**. For instance, if a particular Torsen differential is designed with a 5:1 bias ratio, it is capable of applying up to five times more torque to the wheel that has good traction.

These devices are often used in high-performance all-wheel-drive vehicles. Like the viscous coupling, they are often used to transfer power between the front and rear wheels. In this application, the Torsen is superior to the viscous coupling because it transfers torque to the stable wheels before the actual slipping occurs.

However, if one set of wheels loses traction completely, the Torsen differential will be unable to supply any torque to the other set of wheels. The bias ratio determines how much torque can be transferred, and five times zero is zero.

4-Wheel Drive



Audi Quattro pioneered 4WD technology in 1980 not only dominated rally series, its designer also claimed, "One day, 4WD will become as popular as 4-wheel disc brake in today."....



Today, Audi builds 4WD versions for every of models. This S4 is the high-performance version of A4 sedan



But 4WD still links strongly to rally. Rally brings us some superb machines like this Subaru Impreza WRX Ver IV STi.

4-Wheel Drive is a very important and complicated topic in our automotive study. Before discussing its theory and mechanism, we must know its advantages and disadvantages first.

Advantages and Disadvantages

Traction and Grip :

Apparently, 4-wheel drive brings traction and grip to higher level because the tractive effort is shared by 4 wheels instead of two. This enable higher cornering limit, especially in rough roads and wet condition. Since it was introduced in 1980 to rally cars, 4WD proved its superiority in this aspect.

Weight penalty and power loss :

Because the driving mechanism of the additional wheels has frictional loss, 4WD consumes a little bit more power than 2WD cars. Anyway, this is still a fraction compare with the increased weight. Most 4WD systems weigh 50kg-100kg more than a 2WD system, thus deteriorate acceleration as well as fuel consumption.

Steering tendency :

As mentioned in our study of [Handling](#), in theory, permanent 4WD cars generate neutral steering tendency, thanks to the tractive force sharing by all 4 wheels. However, in reality this become much more complicated. Steering tendency can also be corrected by weight distribution, the adjustment of camber and castor, the choice of different size tyres in front and rear etc. Moreover, it is widely agreed that a slight oversteering, if could be accurately controlled by throttle and steering, is even more satisfying than neutral steering. In contrast, most 50:50 permanent 4WD cars can hardly enable oversteering, unless in really slippery surface.

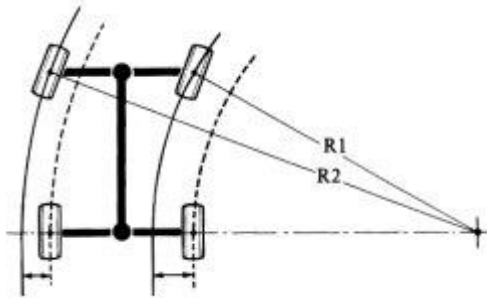
Steering feel :

Depends on tuning, some 4WD cars deliver less steering feel, since the presence of torque in the front wheels may generate slightly torque steer. However, most modern 4WD cars overcome this problem.

Basic layout of 4WD

A modern 4-wheel drive system must have 3 differentials - one in the front axle to distribute torque between the left and right front wheels, one in the rear axle again responsible for torque distribution, the third one, called **Centre Differential**, distributes torque between front and rear axles.

We all know the objective of differential. During cornering, the outside wheels have to travel faster than the inside wheels, therefore we need a differential to distribute different torque to the wheels. For a 4WD car, we in addition need the **Centre Differential** because the front wheels have to travel faster than the rear wheels. The following diagram illustrates this :



If without the centre differential, the non-conformance of front and rear wheel speed will lead to tyre slip as well as energy losses, tyre roar, wear of tyres etc. Therefore centre differential is a must for modern cars.

LSD - the core of 4WD technology



This is the LSD used by Subaru Impreza WRX Ver IV STi

However, just the 3-differential layout alone cannot cope with the basic requirement for 4WD - provides superior grip in the worst roads. In real world driving, for instance, when pushing the car over its limit in corner, or running on slippery surface, tyre slip is inevitable. When a wheel loses traction, a normal differential will transfer nearly all the driving torque to that wheel. As a result, the spinning wheel will spin even wilder, but the wheel that having traction will never share driving torque, therefore the car will be difficult to get out of the trouble. This problem occurs in all kinds of car, no matter 2-wheel drive or 4WD, but it is relatively more important to 4WD because 4WD cars are designed to run in worse roads or cornering harder.

Therefore 4WD cars (or even many latest 2WD sports cars) need Limited Slip Differential (LSD). A LSD lock up both drive shafts whenever tyre slip occurs, thus helps the car get out of trouble quickly. The result is enhanced stability and even higher cornering limit.

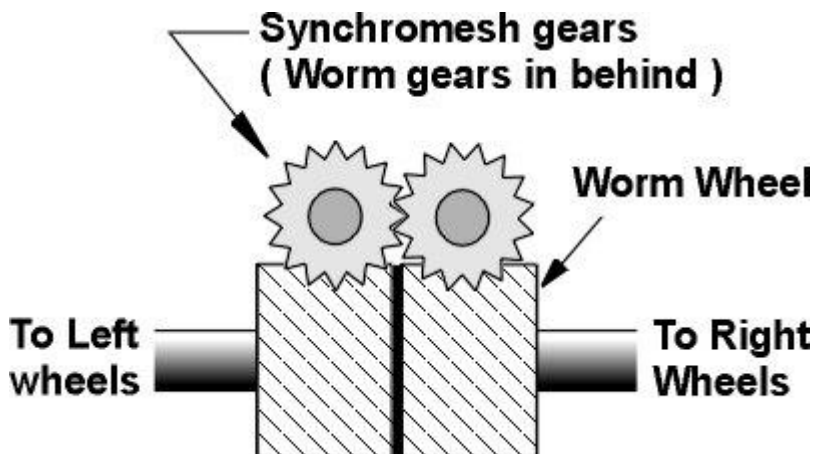
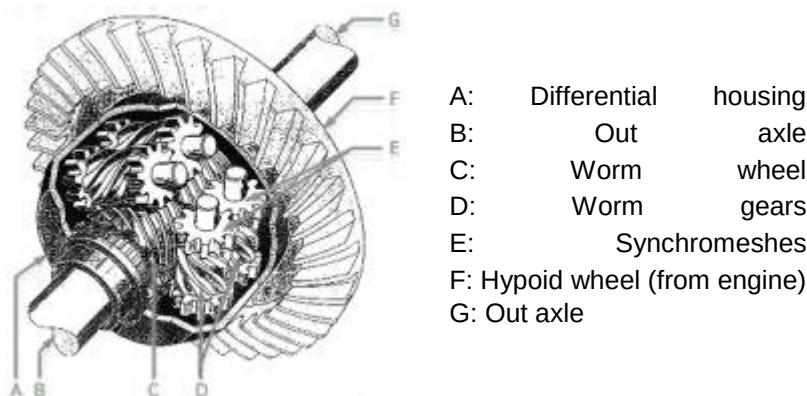
In fact, LSD is the core of 4WD technology. There are several types of LSD: Torsen LSD, Viscous Coupling LSD, VC differential lock and Active LSD. They have different effectiveness, characteristic and cost so that car makers choose them according to their needs. Now we are ready to look deeper inside these 4 types of LSD.

Different types of 4WD

1) Torsen differential - Audi Quattro system*

Being the master of 4-wheel drive, Audi always insists to use the most effective system despite regardless of price. Its Quattro 4WD system* uses a pure mechanical LSD, Torsen differential.

Torsen, means "torque-sensing", was invented by an American company calls Gleason Corporation. Its slip-limiting ability is implemented by cleverly using worm gears / worm wheel pair. This pair has a special characteristic: driving torque can be transferred from worm wheel to worm gear, but not reverse. Otherwise, they will be locked up. It is such characteristic that limit slip.



The above picture explains how Torsen differential works. In normal cornering, i.e., no tyre slip in any wheel, Torsen differential provides the same function as a normal differential. The addition of worm wheel / worm gear pair does not affect speed difference between output shafts. For instance, if the car turns left, the driveshaft to right wheel runs faster than the differential housing, while the driveshaft to left wheel runs slower than the differential housing. The speed difference between left and right worm wheels can be exactly matched in the synchromesh gears. Note that the worm gears / worm wheels pair do not lock up because torque is transferred from worm wheels to worm gears.

When one of the wheels, say the right wheel, loses traction due to poor road surface or whatever reason, the worm gear / worm wheel pair get into effect. At the instant just before they become effective, one must know that by the basic differential theory no torque will be sent to the left wheel, which is with traction. Instead, all the torque will be sent to the spinning right wheel. Then, the fast-rotating right worm wheel will drive its worm gear, through the synchromesh and drive the left worm gear. Now, do you still remember the basic

characteristic of worm gear / wheel pair ? Well, when worm gear drives worm wheel, they will be locked up. As a result, the left worm gear and right worm gear are actually locked together, thus wheels on both side will rotate at the same speed and get the car out of the lose of traction.

Characteristic of Torsen-equipped 4WD

Except the first generation Quattro system that appeared in the early Quattro coupe, most of the subsequent Quattro systems used Torsen differential in center and rear axles. This is rather expensive. However, Torsen-equipped 4WD has many advantages. First of all, its pure mechanical parts react almost instantly to tyre slip. Secondly, it provides linear lock-up characteristic. Thirdly, it is a strictly permanent 4WD system. In normal condition, torque split between front and rear wheels is 50:50 (other ratios are possible, depends on the pitch of worm gears).

Apart from Audi, few other car makers adopted Torsen LSD, mainly because of cost reason. Toyota's rally ace, Celica GT4 was one of the few exception. It used Torsen in the rear axle. This might be part of the reason why it was so expensive over competitors.

Advantage: Quick response, permanent 4WD

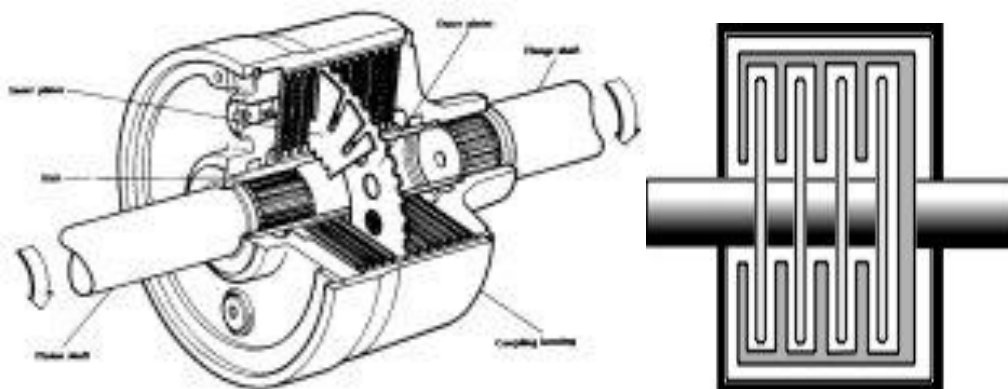
Disadvantage: Pricey, torque split not variable

Who use it ? All non-Golf-based Audi quattro models, Toyota Celica GT4, Hummer etc.

Note: * the "Quattro" mentioned here is the traditional Torsen system marketing in the name Quattro. That includes all Quattro models until the arrival of Audi TT (which uses the Haldex system). Since then the name Quattro becomes a marketing trade mark rather than indicating the actual mechanism. At the time of writing, all Audi Quattro models, excluding the Golf-based A3, S3 and TT, still employs the traditional Torsen system.

2) Viscous-Coupling differential

Viscous Coupling center LSD is commonly used in many simple 4WD systems. One of the earliest examples was Volkswagen's Syncro system.



Inside a viscous coupler as shown in the right hand side picture, there are many circular plates positioning very close to each other. Both drive shafts connect to roughly half of the plates in an alternating sequence as shown. The sealed differential housing is fully contain of a high viscosity liquid, which has a strong tendency to "visco" those plates together.

In normal condition, front and rear axles run at roughly the same speed so the plates and viscous liquid are relatively stable to each other. When tyre slip occurs in one of the axle, that means the alternating plates run at different speed, viscous liquid will try to visco them together. As a result, torque is transferred from the faster driveshaft through the liquid to the slower driveshaft. The greater the speed difference, the larger the torque transfer. As a result, limited slip function is implemented.

Characteristic of Viscous Coupling center differential

Note that Viscous-Coupling LSD is a speed-sensing device: under no-slip condition, no torque will be sent to another axle. Whenever slip occurs, theoretically up to 100% torque can be sent to any axle, depending on the traction difference between front and rear axle. Therefore it is a **part-time 4WD**.

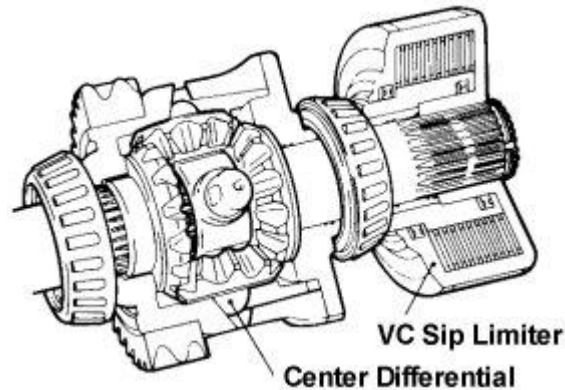
Being a part-time 4WD, it does not have the neutral steering of a permanent 4WD can obtain. For cars based on rear-wheel drive models, such as Porsche 911 Carrera 4, this is not a real problem - as normally

the car runs like a RWD car thus is capable to deliver the desirable throttle oversteer . However, for other front-wheel drive-based cars like VW Golf Syncro and Volvo 850 AWD, the part-time 4WD can do nothing to correct their understeering manner. This is the first disadvantage.

The next problem is the delay before the 4WD get into effective. Since viscous liquid is not a fixed medium (unlike gear), it takes time and speed difference to be effective. The function between speed difference and torque transfer is an exponential function - that means in the early stage of slip, torque transfer remains near zero.

To cure this problem, most manufacturer varies the final drive ratio such that introduce a slightly speed difference even in normal condition. As a result, the car actually runs with 95:5 torque split between front and rear. This shorten the delay time. However, it is still impossible to match the pure mechanical Torsen LSD.

It might be less effective than Torsen system, but it is certainly the cheapest, so we can find it in many mass production 4WD cars.



Advantage: Cheap and compact

Disadvantage: Part-time 4WD only. Normally feels like 2WD.

Who use it ? VW Syncro, Lamborghini Diablo VT, Porsche 993/996 Carrera 4 and Turbo, Volvo 850 AWD etc.

3) Viscous Coupling Differential Lock

While Torsen 4WD is too expensive, Viscous-Coupling LSD is part-time only, most 4WD cars, including the rally ace Celica GT4, Subaru Impreza, Mitsubishi Lancer and Ford Escort RS Cosworth adopted another kind of center differential - basically it has a regular center differential which distribute torque to front and rear under normal condition, an additional Viscous Coupling Differential Lock provides anti-slip function when needed.

Characteristic of this system

The Viscous-Coupling Differential Lock is virtually the same as what we have learned earlier, therefore it also has slight delay and non-linear characteristic. However, in reality this might not be as serious as we thought, otherwise it would have been impossible that all the top rally cars use it. Moreover, Viscous-Coupling Differential Lock system is lighter and cheaper than Torsen system, while having superior effectiveness over the part-time Viscous-Coupling LSD system.

Advantage: Good balance between price and effectiveness

Disadvantage: No special flaw

Who use it ?

- Lancia Delta Integrale (with Torsen in rear axle)
- Ford Escort RS Cosworth (with Viscous-Coupling LSD in rear axle)

- Mitsubishi Lancer GSR, 3000 GT VR4. (with Viscous-Coupling LSD in rear axle)
- Subaru Impreza and Legacy manual versions (with Viscous-Coupling LSD in rear axle)
- Toyota Celica GT4 (with Torsen in rear axle)
- Bugatti EB110 (set to 70% rear bias)

4) Active differential

Active differential 4WD is the most sophisticated one available today. Basically, active LSD is actually a multi-plate clutch enabling variable torque split between front and rear axle. The torque split is controlled by computer which gather information about tyre slip and others from many sensors. Depends on design and software, some systems allow more precise control of traction during hard cornering, some achieve desirable understeer / oversteer, some can even make the best use of traction for acceleration and braking during normal conditions. Since active differential was pioneered by Porsche 959, we take the Porsche system as an example.

Porsche 959's PSK system - the most sophisticated

Until today, Porsche 959's PSK (Porsche-Steuer Kupplung) system is still the only one which make use of variable torque split for maximum traction under normal conditions. In most of the time, torque split between front and rear is 40:60, that is, the same as the car's weight distribution. In hard acceleration, weight transfer to the rear axle increases traction in the rear tyres while reduces traction in the front. Then PSK will transfer up to 80% torque to the rear axle in order to make better use of traction. On slippery road (even tyre slip is yet to occur), 50:50 torque split is used. In any time, computer determines the torque split ratio by analysing parameters such as throttle position, steering angle, g-force and even turbo boost. Therefore PSK system provides optimum traction under all conditions, unlike other 4WD systems which can only varies torque split whenever tyre slip occurs.

Mechanism

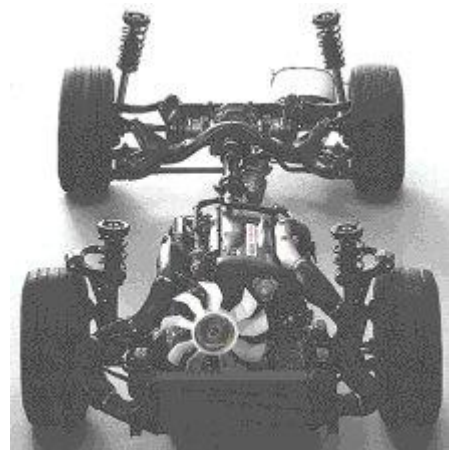
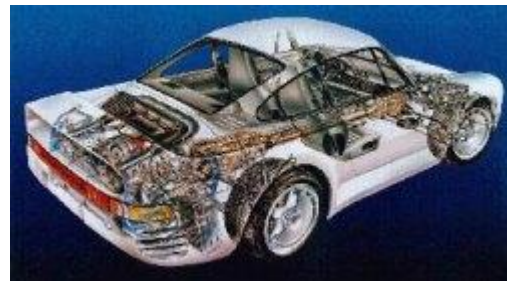
Porsche PSK uses a multi-plate clutch instead of center differential. You may call it a "differential clutch" as well. The multi-plate clutch has 6 pairs of frictional plate, each pair is independently controlled by computer and actuated by hydraulic pressure. This simply equals to 6 independent clutches.

To make this system work, the front and rear driveshafts must run at different speed in normal condition. (so 959 adopted a pair of front tyres with 1% larger diameter than the rear's) Because of the speed difference between front and rear driveshafts, the 2 frictional plates of each independent clutch are rotating relatively to each other. When apply hydraulic pressure to the first clutch, a small amount of torque will transfer to the front axle. But note that the two driveshafts cannot be fully locked up unless all 6 clutches are locked simultaneously.

Now, you may see how it works: lock up 2 clutches, 3 clutches ... and the torque to front wheels will be increased, subsequently, torque split could be 50:50 if all the clutches are fully engaged. Of course, all these action is controlled by computer.

This is only for "normal" condition. Like other 4WD systems, when tyre slip occurs, most of the torque could be sent to either axle.

What about energy loss and wear due to the slipping clutches? As the speed difference is very small, Porsche claimed energy loss is no greater than 0.4% of the power developed by the engine. As for wear, the clutch is dimensioned that it was negligible and caused no problem during the whole life span.



Advantage:	• Variable torque split even in normal condition. Best use of traction. • Since computer monitors and controls everything, theoretically it can cope with any normal or abnormal condition without being limited by the design of mechanical parts. The result is fast response and adaptive.
Disadvantage:	Heavy and expensive
Who use it ?	Porsche 959 only

Mercedes 4-Matic - use under emergency

Mercedes 4-Matic is very much like Porsche's PSK, but it works as a part-time 4WD. In normal condition, the clutches are disengaged so that the car runs just like any rear-wheel drive version. When it lose traction, the computer will signal the clutches to engage progressively so to transfer some torque to the front wheels.

This is rather irrational. It costs even more than Torsen system, but only offers part-time 4WD. However, unlike Porsche's PSK, it is not subjected to any energy loss or wear during normaly conditions, so the clutch can be made smaller and cheaper.

Advantage:	No much
Disadvantage:	Part-time 4WD only; not cheap.
Who use it ?	Mercedes E-class 4-Matic

Nissan Skyline GT-R's ATTESA E-TS PRO

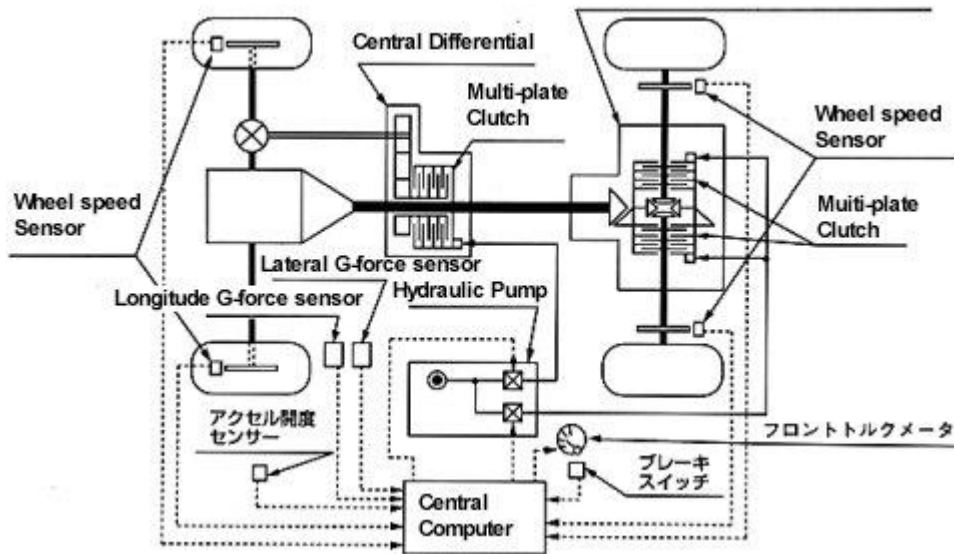
Since R33, Skyline GT-R also uses multi-plate clutch instead of conventional center differential, in addition, as rear differential lock too. Normally it is rear-wheel drive, the front wheels only intervene whenever necessary.

What makes the Skyline system catches my heart is its real world behaviour. Without driving it or reading road test reports, you might not discover its maturity.

As I have mentioned earlier, throttle-controllable oversteering is usually more desirable to real drivers than pure neutral steering. However, what a pity most permanent four-wheel drive cars are inherently unable to deliver power oversteering. Porsche 959 was one of the exception because it had 60% weight bias towards the rear, but for a front-engined car like the Skyline GT-R, the best solution is to leave it as rear-wheel drive in normal conditions.

The clever electronic control system is fed by all the information that Porsche 959 had, such as G-force, boost pressure, throttle position etc, in addition, the speed of individual wheels measured by ABS wheel speed sensors. By these information, the computer knows whether the car is running out of cornering limit or not. If not yet, the multi-plate clutches won't intervene, thus the car can power slide through the corner smoothly. In case out of limit, the multi-plate clutch will engage and send torque to front wheels, increasing traction.

This makes Skyline a rare example of 4WD having oversteering ability.

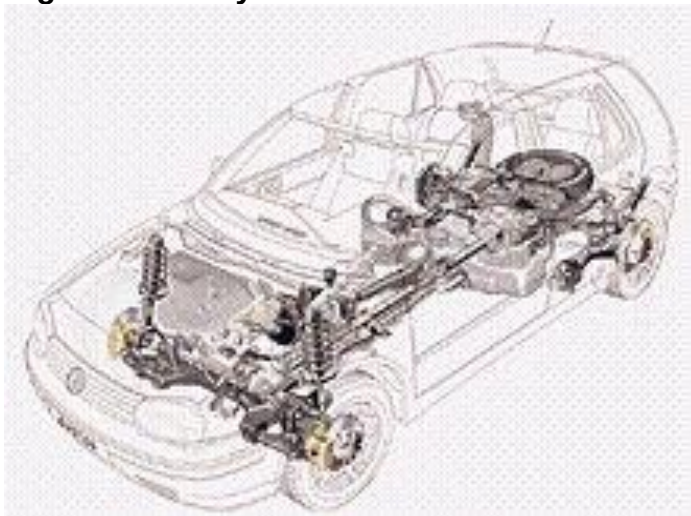


Advantage: Combines RWD's power oversteering with 4WD's maximum cornering limit

Disadvantage: Like other active differential, a bit heavy and expensive

Who use it ? Nissan Skyline GT-R

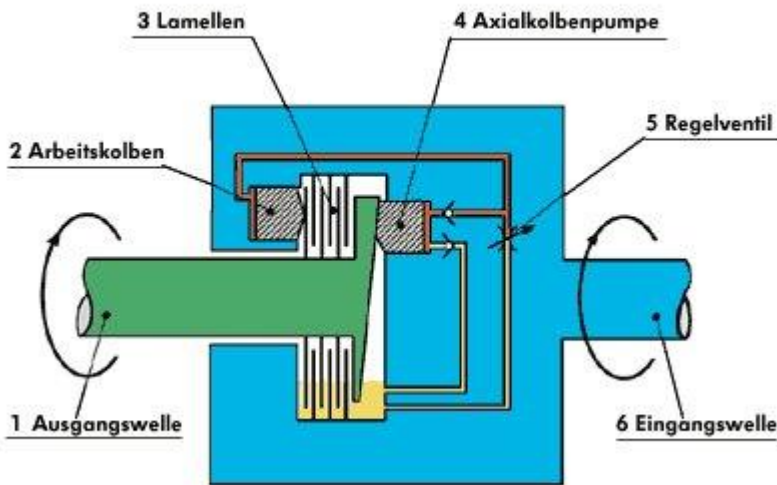
Volkswagen-Haldex system



Since the late 1998, Volkswagen replaced the viscous-coupling Syncro system with a new system called "[4motion](#)". First shown in Audi TT and Golf 4motion, the new system uses a multi-plate clutch center differential developed by a Swedish company, Haldex, and computer software from the Austria 4WD specialist Steyr-Daimler-Puch. At this moment, it is only offered for the transverse-engined Golf IV platform, but there is no technical reason prevents it from applying to Audi's longitudinal-engined models.

The Haldex center differential is similar to Porsche 959's PSK system mentioned in the above, it is only smaller, simpler and cheaper thus making mass production feasible. The center differential is mounted near the rear axle and just in front of the rear differential. As shown in the picture below, its clutch consists of 6 discs

Funktion der Haldex-Kupplung



They are immersed in oil bath to reduce friction. Actuation is made by hydraulic pressure. Normally the input and output shafts rotate with a speed difference (could be implemented by different final drive ratio), therefore the discs are rotating relative to each other. When no pressure is applied, the clutch is not engaged thus torque will not be transferred to the rear axle. Increase the pressure on the multiplate clutch, the latter will be partially engaged, thus sending torque to the rear axle. The more the clutch engages, the more torque transfers to the rear axle.

Computer determines how much torque to be sent to the rear wheels. Normally it is 50:50, but in tight corners when wheels on one of the axles is slipping, the driver can easily feel the torque is transferring from one to another axle. Volkswagen claimed 100% torque could be sent to either axle.

Compare with 959's unit, Haldex's unit has 7 fewer discs in the clutch. This makes the Haldex unit more compact and cheaper. The down side is not capable to handle as much torque (959 had 369 lbft, Audi TT has 206 lbft). Besides, 959's discs were organised as 6 pairs of independent clutches, each actuated by individual hydraulic actuator. The Haldex has just one actuator acting on all six discs, again, this saves weight and cost. However, I suspect if it could vary the amount of torque split as precise as independent clutches.

Based on the journalists comment about the handling of Audi TT and Golf 4motion, it seems that the 4motion system performs even better than the traditional Torsen-differential Quattro. The age of Torsen Quattro is passing away.

Advantage: Inexpensive and quite compact

Disadvantage: Unknown torque-handling ability.

Who use it ? Audi TT, Golf 4motion ... actually all 4WD versions of Golf IV's derivatives

Note: "4motion" is not equal to Haldex system. Volkswagen also use "4motion" to represent the Torsen-LSD system used by Passat. Therefore, "4motion" is actually a marketing nameplate instead of indicating the mechanical design.

The Rise and Fall of 4WD

Jensen FF - the real pioneer of modern 4WD

Whenever talk about 4WD, most people will probably think of Audi. In fact, Jensen, a small British sports car maker, introduced the first modern 4WD system into its Jensen FF grand tourer as early as 1966.

Worked in collaboration with engineering consultant FF Development, Jensen's system employed the so-called "Ferguson Formula" layout, that is, Viscous Coupling differential lock for both the center and rear differentials. This system is still the most popular 4WD system today. Accompany with the world's first anti-

lock brake (though mechanical only), Jensen FF amazed the contemporary auto journalists by its superior stability.

However, without mass production, it was inevitably twice as expensive as a Jaguar E-type. Technical breakthrough it certainly had, but sales remained poor until production terminated in 1972.

Audi Quattro - successfully applied 4WD in mass production

In 1980, Audi unveiled a coupe based on the 80 sedan but equipped with a 4WD system called Quattro. Technically speaking, this first generation system lagged behind Jensen's because it used manually lock-up center and rear differentials instead of Jensen's LSD. Anyway, soon Audi upgraded Quattro to use Torsen center and rear LSD.

To establish reputation, Quattro appeared in World Rally Championship even before the road car delivered to customers. It immediately won the title in 1980 and continued dominating in the next two years.

The road car also won appreciation about its handling from all over the world. The world-wide market for mass production 4WD road car started to take off as a result.



Golden period - 1983-1993

As Audi Quattro Sport succeeded in rallying, other major car makers also developed 4WD rally cars to compete in the Group B WRC rally. Since Group B cars were as powerful as 500 hp, 4WD must be superior than 2WD to handle so much power in the worst route. As a result, any participants should develop 4WD if they want to win. From 1983 to 1985, we saw many exotic 4WD rally cars appeared - Peugeot 205 T16, Lancia Delta S4, Ford RS200, Rover Metro 6R4 etc. This was one of the examples that motor racing accelerated the development of road car technology.

Group B rally was cancelled in 1986 as too many fatal accidents occurred. Instead, FIA established the less-powerful Group A that required a minimum production of 5,000 units and limited modifications. Such regulations led to more practical 4WD road cars developed, such as Lancia Delta Integrale, Ford Escort RS Cosworth, Toyota Celica GT4, Mitsubishi Lancer GSR and Subaru Impreza WRX.

In parallel to the rally car development, Audi started to put 4WD into every sedan models - 80, 90, 100 and 200, and all the subsequent models. The objective was to enhance active safety and security in wet / snow conditions rather than encourage fast cornering. Other contemporary sedans such as BMW 325 iX, Ford Sierra XR4x4, Peugeot 405 4x4 and all the non-turbo Subaru also followed this way.

On the other hand, 4WD also found opportunity in high performance versions of FWD cars because the combination of high power and FWD always result in excessive torque steering and tyre slip. Therefore they were upgraded to 4WD. Opel Calibra turbo, Alfa 155 Q4, Mitsubishi Galant VR4 and Renault 21 Quadra turbo belonged to this kind.

Depression - 1994-1999

Since 1994, more and more car makers stopped developing 4WD version of their new generation models. This was mainly due to the emergence of traction control and stability control. As I have mentioned, most sedans adopted 4WD to enhance wet / snow road safety, this also can be implemented by traction control and stability control. Since these electronic devices use ABS's hardware, they could be a lot cheaper than 4WD and have virtually no penalty to weight and fuel consumption.

In fact, 4WD is still superior because it really enhances cornering grip and cornering limit, while traction control and stability control just limit the engine output and apply braking to prevent the car from exceeding its traction limit. Therefore 4WD must corner faster and more stable.

However, this cannot justify for the high cost, so most major car makers dismissed 4WD. [Here](#) is a list of 4WD cars offering in 1992, in contrast to those offering in 1998. As you can see, Alfa, BMW, PSA, Lancia, Opel, Renault and Mazda completely stopped making 4WD cars, leaving Audi / VW and Subaru to be the only major 4WD makers, while Volvo is the only new participant in the past 5 years.

Year 2000 and Future - a revival ?

It seems that 4WD becomes popular again as SUV (Sport Utility Vehicle) and RV (Recreational Vehicle) take off. In America, nearly half of the new cars sold now are 4-wheel-drive SUV, although most of them actually employ old-fashion system without LSD. In Japan, nearly all new cars offer a 4WD version to choose from, and this also include the tiny K-cars !

Audi also sold most of its cars in America with Quattro installed, this led to the revival of 4WD BMW 3-series in 2000. Will 4WD be revived ? Let's see.



Audi A8, many people think it is unnecessary to use 4WD. In fact, A8 is the only 4WD car in its class.

4WD cars offering in Europe in 1992 vs 1998

1992	1998
Alfa Romeo 33 Q4	Died
Alfa Romeo 155 Q4	Died
Alfa Romeo 164 Q4	Died
Audi 80 quattro / Coupe quattro / S2	Replaced by A4 quattro / S4
Audi 100 quattro / S4	Replaced by A6 quattro
Audi V8	Replaced by A8
BMW 325 iX	Died
BMW 525 iX	Died
Bugatti EB110	Died
Citroen AX 4x4	Died
Citroen BX 4x4	Died
Fiat Panda	Still surviving
Ford Escort RS Cosworth	Died
Ford Sierra XR4x4	Replaced by Mondeo 4x4
Ford Sierra / Sapphire RS Cosworth	Died
Ford Scorpio 4x4	Died
Lamborghini Diablo VT	Still in production
Lancia Delta HF Integrale	Died
Lancia Dedra HF Integrale	Died
Mazda 323 GT-R	Died

Mazda 626 4x4	Died
Mercedes W124 4-Matic	Replaced by E-class 4-Matic
Mitsubishi Galant VR4	New Galant VR4
Mitsubishi Eclipse GSX	Still in production
Mitsubishi 3000GT VR4	Still in production
Mitsubishi Sigma	Died
Nissan Sunny GTI-R	Died
Nissan Skyline GTR	New Skyline GTR
Opel Calibra 4x4	Died
Peugeot 405 4x5	Died
Porsche 911 (964) Carrera 4	993 turbo, 996 Carrera 4.
Renault 21 Quadra	Died
Renault Safrane Biturbo	Died
Subaru Justy	Died
Subaru Impreza	Still in production
Subaru Legacy	New Legacy
Subaru SVX	Still surviving
Toyota Celica GT4	Still surviving
Volkswagen Golf Syncro	New Golf Syncro
Volkswagen Passat Syncro	New Passat Syncro
-----	Volvo S70 AWD

Remark : this table does not take SUV, MPV and K-Car into account.

4-Wheel Steering

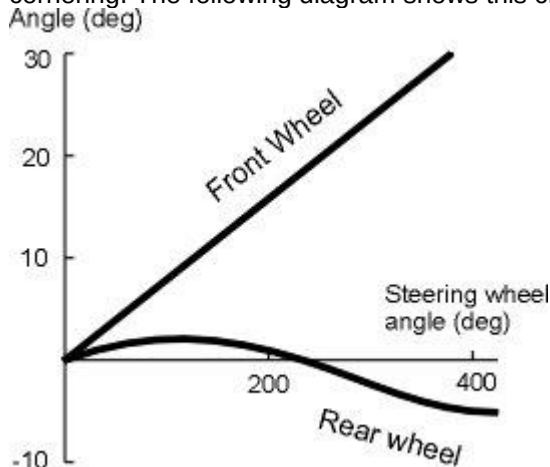
History of 4WS

Actually, 4-wheel steering is not a complicated concept, it is meaningless to know who "invented" it. The most difficult is to implement it effectively, with sufficient benefit to justify the additional cost. The first one to do that was probably Mercedes-Benz. In 1938, it made a cross-country military vehicle called 170VL, which steered the rear wheels reverse to the front wheels in order to shorten turning radius. But Mercedes never applied 4WS in its road cars. The first 4WS mass-production road car was Nissan Skyline (not GT-R) in around 1985. Unlike the Mercedes, it steered the rear wheels in the same direction as the front wheels with a maximum angle of 0.5 degree, that helped stability. However, Skyline's system does not qualified for our definition of 4WS, because it simply steered the whole rear suspension mounting sub-frame by hydraulic.

Honda Prelude - new era of 4WS

Therefore the first decent production 4WS car was Honda Prelude (1987). The most special thing and also a patented innovation is: the steering angle of rear wheels depends on the front wheels. When turning the

steering wheel, initially the rear wheels steer slightly, at most 1.7 degree, in the same direction as the front wheels. This improves stability during high speed turning or lane changing. Continue turning the steering wheel a lot will reverse the direction of rear wheels. This is used to sharpen the response of low speed cornering. The following diagram shows this characteristic:



Prelude's mechanism was very simple, just uses eccentric shaft combine with planetary gear, purely mechanical. Electronic-aided mechanism replaced it in the next generation Prelude in 1992.

4WS - from popular to declining

From the late 80s to today, 4WS remained to be uniquely adopted by Japanese car makers. Western car makers seemed to be not very interested (Audi was rumoured to be developing 4WS for A8, but it did not realise) Even Japanese themselves are starting to lose interest -

- Toyota: the no. 1 maker has never put 4WS into production.
- Nissan: after the death of 300ZX, dropping 4WS from Infiniti Q45, only Skyline remains offering 4WS.
- Honda: as active differential appeared in the latest Prelude, 4WS disappeared in this company.
- Mitsubishi: after Galant VR4 and Diamante dropped 4WS, only the old GTO still has 4WS.
- Mazda: 929 is still the only 4WS model.

4WS is seriously threatened by Electronic Stability Control and Yaw Control, both of which can correct understeer / oversteer like 4WS but without much additional cost and weight penalty.

Skyline's Super HICAS

However, Nissan Skyline GT-R still proves that 4WS is worthy for demanding driving. Aided by computer, its Super HICAS system enable tightly-controlled power slide that cannot be implemented by any alternatives. When attacking a corner, the rear wheels will steer in reverse first in order to sharpen the initial steering response. Then, when sensors sense that the car responds to steering, the rear wheels will steer in the same direction as the front wheels, thus immediately introduces rear-tyre slip which help adjusting the attacking angle. Since the computer is monitoring the whole process, the amount of oversteering is always under check. You need not to be afraid of losing control.



ABS (Anti-lock Braking System)

You might think that optimal braking is implemented by completely locking all the wheels. No, law of physics tells us that the coefficient of friction between the ground surface and a static object is always greater than a moving object. If the tyres are sliding on the road surface, the friction between road and wheel will not be

maximum. Therefore, the maximum braking occurs when the wheels are braked up to the level that the wheels just do not slide.

To ensure the shortest stopping distance, ABS applies intermittent braking in very high frequency. This avoids complete lock up of wheels, thus giving the name "Anti-Lock Braking System".

Another advantage of ABS is letting the driver to keep controlling the car during braking. Before ABS appeared, cars lock up during braking, thus unable to be steered to avoid collision. With ABS, while slowing down the car, the driver can simultaneously try to steer away from the obstacle in front.

To implement anti-lock braking, ABS system employs speed sensors for individual wheels. If the wheel speed detected differs from the vehicle speed, that means the wheel is sliding, thus the computer will signal the corresponding brake to loose until sliding disappears. The computer will also compare the speed of all wheels, if one or more of them run considerably faster than others, that means the car is losing control, it will apply more brake to that wheel to correct the driving path.

ABS was originated in aeroplanes. It was developed in order to shorten the distance necessary for landing. It did not appear in road cars until 1966, when Jensen FF (the first 4WD road car) installed a system developed by Dunlop. That system, called Maxaret, did not employ computer as well as wheel speed sensors. It just employed electronic sensors to avoid locking the disc brakes. Anyway, road testers immediately found its superiority over conventional brakes.

- BMW applied ABS to its road cars in 1979. Then motorcycle in 1987.
- Bosch launched the modern computerised ABS in the early 80s. Mercedes and BMW included it as option of their top of the range.
- In 1985, Ford Granada Scorpio took it as standard equipment, while Chevrolet Corvette made it a very common option. As production scale increased, ABS became cheaper and popular.
- In the mid-80s, Lucas Girling and AP also developed their low price ABS for cars like Ford Escort and Fiat Uno. Both served only the front wheels.
- Today, even mini cars offer ABS as standard.

Significance of ABS

Not only enhance braking, ABS sensors, computer and hydraulic pump also serve as the hardware for Traction Control, Electronic Stability Control and Artificial LSD (read these topics in the following paragraphs). If not ABS is so popular, these new technology might not have appeared.

Traction Control

Saab 9000's TCS system was one of the earliest Traction Control systems applied to road cars. To Saab 9000 and other front-wheel drive cars, hard acceleration used to cause trouble to the driving wheels. Hard acceleration always causes weight transfer which lightens the front end. This reduces the traction of front wheels, thus causing wheel spin. When wheel spin occurs, the friction between wheels and ground drops considerably so that it takes longer to launch. Moreover, wheel spin also introduces instability.

Besides, the combination of a powerful engine and 2WD always result in wheel spin. This also calls for the need of Traction Control.

Like other subsequent Traction Controls, Saab's TCS prevents wheel spin by lowering engine output or even applying brakes to the spinning wheels. All these actions are tightly monitored by the microprocessor. Based on essentially the same hardware as ABS, in collaboration with engine management system, TCS adds little cost.

Electronic Stability Control (eg. Mercedes ESP)



Electronic Stability Control won't be so well-known without Mercedes A-Class. After the roll-over incident, Mercedes fitted ESP to this car as standard equipment.

To understand the purpose of Electronic Stability Control, we must learn some basic steering theory first.

Understeering and Oversteering

When a driver turns the steering wheel, he would expect the car steers exactly the same direction as he has already inputted, no less and no more. However, in reality, this so-called "neutral steering" is very difficult to obtain. Weight distribution, FWD / RWD / 4WD, suspension geometry, choice of tyres etc. can introduce non-neutral steering.

Correct understeering and oversteering by ESC

Electronic Stability Control appeared in just several years ago. It was (again) pioneered by Bosch, helped by its first client, Mercedes-Benz, as they tested the ESC-equipped 600SEC coupe extensively in snow. Its objective is to correct extreme understeering and oversteering when the car corners too fast or on slippery surfaces. In other words, it ensures cornering stability.

Stability control is the next logical evolution of ABS and Traction Control. It has ABS's hardware and two additional sensors: steering-wheel angle sensor, which measures the rate the steering wheel is turning, and yaw sensor, which measures the rate the vehicle is actually turning. By comparing them, computer will know if the vehicle is oversteering or understeering.

On slippery surfaces or aggressive maneuver, if the car understeer seriously, the computer will actuate the brakes on the inside rear wheel, just hard enough and just long enough to correct the steering behaviour. Some systems like Bosch's can also reduce the engine output to cooperate.

When the car oversteer seriously, the outside front wheel will be braked instead.

Limitation of ESC

Unlike 4WD and 4WS, Electronic Stability Control cannot raise cornering limit. It just prevent the car from exceeding the limit through intelligent control of individual wheels. Therefore, it is a security system for unexpected conditions.

Unless you are a novice driver or your car is very unbalanced, ESC cannot help you to corner faster. By opposite lock and cooperation of braking, human can do better than computer, at least until today. Therefore, most good drivers like to switch off ESC for weekend driving. As a safety backup device for daily drive, however, ESC is worthwhile.

Different Versions of ESC

- Mercedes' ESP (Electronic Stability Program): by Bosch.
- BMW's DSC (Dynamic Stability Control) and CSC (Cornering Stability Control): also by Bosch, but different program leads to slightly different character.
- GM's "Active Handling Chassis Control System": by Delphi. It is installed in Corvette and emphasis less intervention, thus allows more oversteering that a sports car requires. Cadillac Seville has a less sporty system.
- Others: Honda VSA, Mitsubishi ASC, Toyota and more car makers also developed their ESC recently.

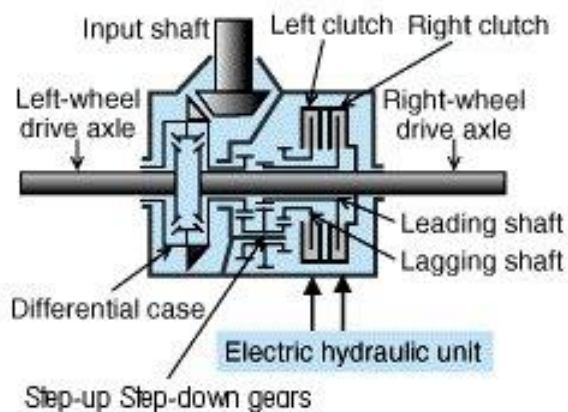
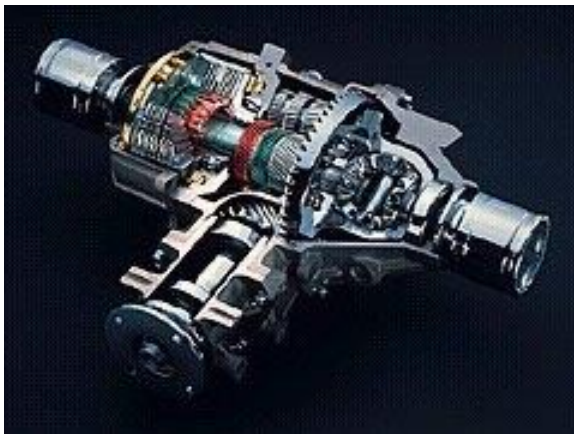
Artificial LSD : **Bosch-Porsche ABD as an example**



Limited Slip Differential (LSD) can be artificially implemented by using ABS hardware with additional program. Here I take Bosch-Porsche's ABD (Automatic Braking Differential) as an example.

When ABS sensor detected tyre slip in one wheel, ABD program will actuate the brake on that wheel. As the wheel locks up, differential will transfer torque to the other wheel which has traction, so the car can get out of trouble quickly. That's all !! Too simple ?

Active Differential - **Mitsubishi AYC as an example**



Somewhat similar to ABD, but Active Differential operate all the time during cornering, unlike ABD that operate when tyre slip occurs. According to Honda and Mitsubishi, Active Differential transmit more torque to the outside wheel, thus quicken cornering action. I don't know how effective it eventually will become, but at this stage their Active Differential-equipped cars, Lancer GSR Evo V and Prelude ATTS, have not shown significant advantage.

Anyway, we still spend some time to study it basically, it implements active torque transfer by using the 2 clutches incorporated inside the differential - one of them control the right wheel and one control the left. When computer think it is necessary to transfer more torque to one of the wheels, it tightens the clutch of the opposite wheel, thus more torque will be sent to the desired wheel. Since it uses clutch instead of ABD's brake, it can precisely control the torque distribution, without locking a wheel. This guarantees a smooth operation that can be used all the time.

Latest Brake Development



There's relatively less throughout for brake discs during the past 20-30 years. The most powerful disc brakes are still ventilated, cross-drilled and made of cast-iron, although larger wheels enable larger diameter of brake discs.

For calipers, road cars today still employ single caliper per disc. Each caliper is actuated by up to 4 pistons ("4-pot") or a few racing-biased cars may even employ 6-pot calipers. The caliper

is made in a single piece - so called "monobloc" - and made of aluminium.



Cast-iron, aluminum and carbon-fiber discs

Obviously, cast-iron disc is the heaviest part of a brake - about 8 kg each, or 32 kg per car. Aluminium alloy discs are used in the base Lotus Elise. Though light, they were less resistant to heat and fade, thus more powerful Elises still employ conventional cast-iron disc.

In contrast, carbon-fiber disc is most heat-resisting yet is by far the lightest, however, it requires very high working temperature, otherwise braking power and response will be unacceptable. (it's expensive as well) It was first introduced in Formula One, but applying to road cars seems impractical (F1 cars have warm up lap to bring the discs into appropriate working temperature), although the short-lived French

sports car specialists Venturi made history by applying it to its road cars in the mid-90s.



Porsche's ceramic disc brakes

Recently, Porsche introduced a breakthrough to the 996 Turbo - ceramic disc brakes. Ceramic disc is highly heat and fade-resisting. Moreover, it is just 4 kg each, or half of a conventional cast-iron disc, thus save 16 kg per car. This benefit performance as well as ride quality (because of lower unsprung weight). The ceramic disc is based on specially treated

carbon-fibers that are siliconized at 1,700°C in a high-vacuum process.

Accompany with a new metallic brake pad, Porsche claimed it provides superior braking power yet requires less effort, thus does not require brake assist. The pad does not absorb water, hence excellent response under wet conditions.

Brake Assist

According to Mercedes, most drivers (especially women) do not brake as hard as they would have thought during accident. Analysing the Braking Pedal Effort vs Time curve will find the braking pedal effort easily fade because of the lack of physical effort. Some people's feet are not accelerative enough to brake hard quickly. As a result, collision may still happen no matter how strong the brakes are.

Therefore many Mercedes cars are installed with BAS (Brake Assist System) to artificially accelerate and enhance the braking effort.

Safety + Crash

Airbags

For years, the trusty seat belt provided the sole form of passive restraint in our cars. There were debates about their safety, especially relating to children, but over time, much of the country adopted mandatory seat-belt laws. Statistics have shown that the use of seat belts has saved thousands of lives that might have been lost in collisions.

Air bags have been under development for many years. The attraction of a soft pillow to land against in a crash must be very strong -- the first patent on an inflatable crash-landing device for [airplanes](#) was filed during World War II! In the 1980s, the first commercial air bags appeared in automobiles.

Since model year 1998, all new cars have been required to have air bags on both driver and passenger sides. (Light trucks came under the rule in 1999.) To date, statistics show that air bags reduce the risk of dying in a direct frontal crash by about **30 percent**. Newer than steering-wheel-mounted or dashboard-mounted bags, but not so widely used, are seat-mounted and door-mounted side air bags. Some experts say that within the next few years, our cars will go from having dual air bags to having six or even eight air bags! Having evoked some of the same controversy that surrounded seat-belt use in its early years, air bags are the subject of serious government and industry research and tests.

Before looking at specifics, let's review our knowledge of the **laws of motion**. First, we know that moving objects have **momentum** (the product of the mass and the velocity of an object). Unless an outside **force** acts on an object, the object will continue to move at its present speed and direction. Cars consist of several objects, including the vehicle itself, loose objects in the car and, of course, passengers. If these objects are not restrained, they will continue moving at whatever speed the car is traveling at, even if the car is stopped by a collision.

Stopping an object's momentum requires force acting **over a period of time**. When a car crashes, the force required to stop an object is very great because the car's momentum has changed instantly while the passengers' has not -- there is not much time to work with. The goal of any supplemental restraint system is to help stop the passenger while doing as little damage to him or her as possible.

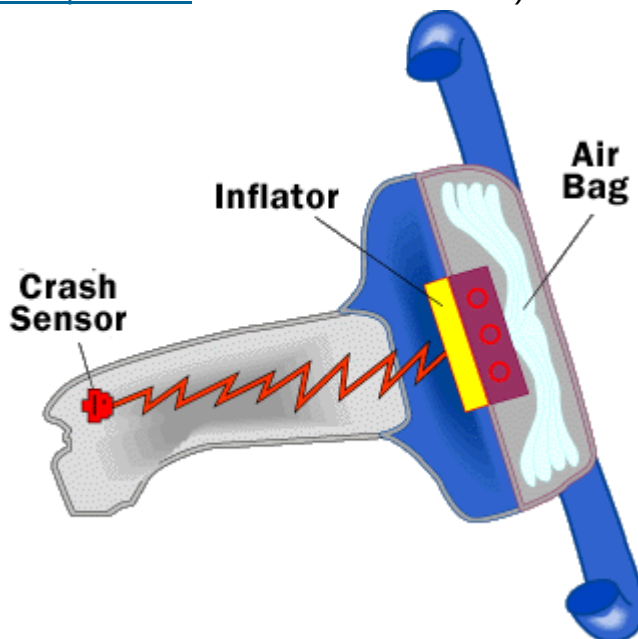
What an air bag wants to do is to slow the passenger's speed to zero with little or no damage. The constraints that it has to work within are huge. The air bag has the space between the passenger and the [steering wheel](#) or dash board and a fraction of a second to work with. Even that tiny amount of space and time is valuable, however, if the system can slow the passenger evenly rather than forcing an abrupt halt to his or her motion.

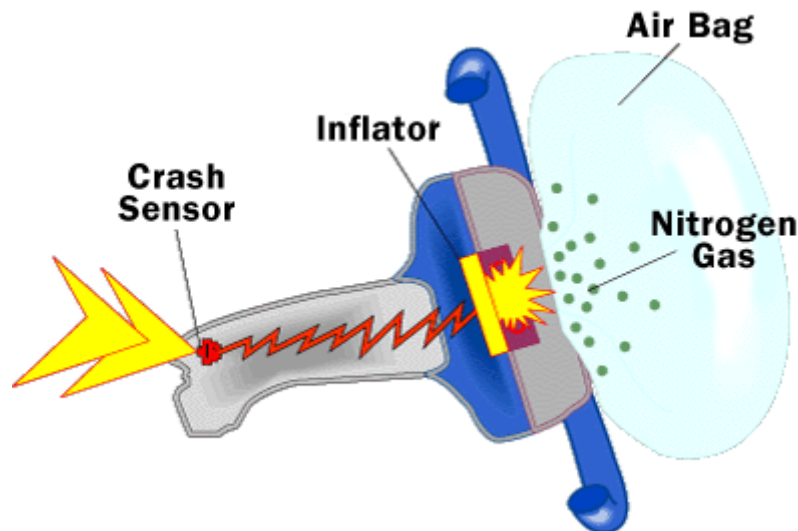
There are three parts to an **air bag** that help to accomplish this feat:

- The **bag** itself is made of a thin, nylon fabric, which is folded into the steering wheel or dashboard or, more recently, the seat or door.

- The **sensor** is the device that tells the bag to inflate. Inflation happens when there is a collision force equal to running into a brick wall at 10 to 15 miles per hour (16 to 24 km per hour). Sensors detect the crash using a **mechanical switch** that closes when a mass shifts and an electrical contact is made. Electronic sensors use a tiny **accelerometer** that has been etched on a silicon chip.
- The air bag's **inflation system** uses the rapid pulse of hot **nitrogen gas** from the chemical reaction of **sodium azide (NaN_3)** and **potassium nitrate (KNO_3)** to inflate the bag ([full chemical equation](#)).

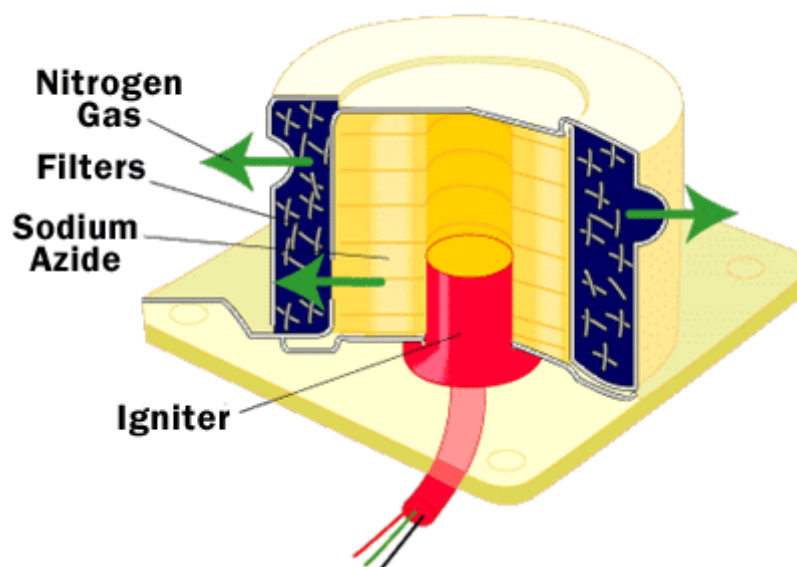
The inflation system is not unlike a solid rocket booster (see [How Rocket Engines Work](#) for details). The air bag system ignites a **solid propellant**, which burns extremely rapidly to create a large volume of gas to inflate the bag. The bag then literally **bursts** from its storage site at up to 200 mph (322 kph) -- faster than the blink of an eye! A second later, the gas quickly dissipates through tiny holes in the bag, thus **deflating** the bag so you can move. (Try this [fun experiment](#) to see how this works.)





The air bag and inflation system stored in the steering wheel

Air Bag Inflation Device



The inflation system uses a solid propellant and an igniter.

Even though the whole process happens in only **one-twenty-fifth of a second**, the additional time is enough to help prevent serious injury. The **powdery substance** released from the air bag, by the way, is regular cornstarch or talcum powder, which is used by the air bag manufacturers to keep the bags pliable and lubricated while they're in storage.

According to [Scientific American](#), the idea of using a **rapidly inflating cushion** to prevent crash injuries had a long history before the U.S. Department of Transportation called for the equipment to be adapted for automobiles in the 1980s. The first patent on an inflatable crash-landing device for airplanes was filed during World War II. Early efforts to adapt the air bag for use in cars bumped up against prohibitive prices and technical hurdles involving the storage and release of **compressed gas**. Researchers wondered:

- If there was enough room in a car for a gas canister
- Whether the gas would remain contained at high pressure for the life of the car
- How the bag could be made to expand quickly and reliably at a variety of operating temperatures and without emitting an ear-splitting bang

Small **solid-propellant inflators** came to the rescue in the 1970s. These devices initiated the chemical reaction that released hot nitrogen gas into the bag.

In the early days of auto air bags, experts cautioned that the new device was to be used in tandem with the seat belt. Seat belts were still completely necessary because air bags worked only in front-end collisions occurring at more than 10 mph (6 kph). Only seat belts could help in side swipes and crashes (although side-mounted air bags are becoming more common now), rear-end collisions and secondary impacts. Even as the technology advances, air bags still are only effective when used with a lap/shoulder seat belt!

Safety

It didn't take long to learn that the force of an air bag can hurt those who are too close to it. Researchers have determined that the [risk zone for driver air bags](#) is the first **2 to 3 inches** (5 to 8 cm) of inflation. So, placing yourself 10 inches (25 cm) from your driver air bag gives you a clear margin of safety. Measure this distance from the center of the steering wheel to your breastbone. If you currently sit less than 10 inches away, you can adjust your driving position in the following ways:

- Move your seat to the rear as far as possible while still reaching the pedals comfortably.
- Slightly recline the back of your seat. Although car designs vary, most drivers can achieve the 10-inch distance even with the driver seat all the way forward by slightly reclining the back of the seat. If reclining the seat makes it hard to see the road, you can raise yourself up by using your car's seat-raising system (not all cars have this!) or a firm, non-slippery cushion to achieve the same effect.
- Point the air bag toward your chest, instead of your head and neck, by tilting your steering wheel down (this only works if your steering wheel is adjustable).

The rules are different for **children**. An air bag can seriously injure or even kill an unbuckled child who is sitting too close to it or is thrown toward the dash during emergency [braking](#). Experts agree that the following [safety points](#) are important:

- Children 12 and under should ride buckled up in a properly installed, age-appropriate rear car seat.
- Infants in rear-facing child seats (under one year old and weighing less than 20 pounds / 9 kg) should never ride in the front seat of a car that has a passenger-side air bag.
- If a child over one year old must ride in the front seat with a passenger-side air bag, he or she should be in a front-facing child safety seat, a booster seat or a properly fitting lap/shoulder belt, and the seat should be moved as far back as possible.

Deactivation

In response to concerns about children -- and others, especially smaller people -- being killed or seriously injured by malfunctioning or overly powerful air bags, the [National](#)

[Highway Traffic Safety Administration](#) (NHTSA) in 1997 issued a final rule to allow auto manufacturers to use lower-powered air bags. This rule permits air bags to be **depowered** by 20 to 35 percent. In addition, starting in 1998, repair shops and dealers were allowed to install **on/off switches** that allow air bags to be deactivated. Vehicle owners could now be authorized (by the NHTSA) to get on/off switches installed for one or both air bags in their car if they (or other users of their car) fell into one or more of these specific risk groups:

- **For both driver and passenger sides** - Individuals with medical conditions in which the risks of deploying the air bag exceed the risk of impact in the absence of an air bag
- **For the driver side** (in addition to medical conditions) - Those who cannot position themselves to properly operate their cars at least 10 inches (25.4 cm) back from the center of the driver air bag cover
- **For the passenger side** (in addition to medical conditions) - Individuals who need to transport a baby in a rear-facing child restraint in the front seat because the car has no rear seat, the rear seat is too small to accommodate a rear-facing child seat or because it's necessary to constantly monitor a child's medical condition
- **For the passenger side** (in addition to medical conditions) - Individuals who need to carry children between one and 12 years old in the front seat because (a) the car has no rear seat, (b) the vehicle owner must carry more children than can fit into the back seat or (c) because it's necessary to constantly monitor a child's health

If you would like to get an on-off switch installed in your car, you need a copy of NHTSA's brochure, "Air Bags and On-Off Switches: Information for an Informed Decision," and the accompanying form, **Request for Air Bag On-Off Switch**. You can find these on the [NHTSA Web site](#), as well as at AAA clubs, new-car dealers and state motor vehicle departments. The NHTSA will send you a letter of authorization that you can take to a repair shop. (Before you bother with all this, you should check with your auto dealer or repair shop to see if an on-off switch is available for your car.) Some **retrofit on-off switches** can be found and used if federal requirements are met -- switches must be operated by a key and equipped with warning lights to indicate whether the bags are turned off or on.

Obviously, even you have the option of turning it off, the air bag should be left on for drivers who can sit at least 10 inches back. For those who can't (even with the suggestions listed above), the bag can be turned off. A group of doctors at the National Conference on Medical Indications for Air Bag Deactivation considered the medical conditions commonly reported in letters to the NHTSA as possible justification for turning off air bags. They did not, however, recommend turning off air bags for relatively common conditions, such as pacemakers, [eyeglasses](#), [angina](#), [emphysema](#), [asthma](#), mastectomy, previous back or neck surgery, advanced age, osteoporosis, arthritis or [pregnancy](#).

Generally speaking, you can't deactivate your air bag without installing a retrofit on-off switch. However, if a retrofit on-off switch is not yet available (from the vehicle manufacturer) for your car, the NHTSA will authorize air bag deactivation on a case-by-case basis under appropriate conditions. Never try to disable the bag yourself -- remember, this is no soft cushion! It packs a wallop and can hurt you when you don't know what you're doing.

As for factory-installed on-off switches, the NHTSA allows car manufacturers to install **passenger air bag on-off switches** in new vehicles under limited circumstances -- only if

the vehicle has no rear seat or if the rear seat is too small to accommodate a rear-facing child safety seat. And manufacturers are not currently allowed to install on-off switches for the driver air bag in any new vehicle. Why these rules? The NHTSA decided against widespread factory-installed on-off switches for fear that they would become standard equipment in all new vehicles -- even those purchased by people not in at-risk groups. They also saw the integration of on-off switches into new cars (and the subsequent redesign of instrument panels) as something that would divert resources from the development of safer, more advanced air bag systems.

The Future of Air Bags

Activities aimed at maintaining and improving the lifesaving benefits of air bags are in full swing. New NHTSA-sponsored tests use improved "[dummy](#)" injury criteria based on new knowledge and research.

Until recently, most of the strides made in auto safety were in front and rear impacts, even though **40 percent** of all serious injuries from accidents are the result of side impacts, and 30 percent of all accidents are side-impact collisions. Many carmakers have responded to these statistics (and the resulting new standards) by beefing up doors, door frames and floor and roof sections. But cars that currently offer **side air bags** represent the new wave of occupant protection. (In 1995, the [Audi 850 series](#) was the first car to feature six air bags, including seat-mounted side air bags for the front and rear passengers.) Engineers say that designing effective side air bags is much more difficult than designing front air bags. This is because much of the energy from a front-impact collision is absorbed by the bumper, hood and engine, and it takes almost 30 to 40 milliseconds before it reaches the car's occupant. In a side impact, only a relatively thin door and a few inches separate the occupant from another vehicle. This means that door-mounted side air bags must begin deploying in a mere **5 or 6 milliseconds!**

[Volvo engineers](#) experimented with different ways of mounting side air bags and chose seat-back installation because that protects passengers of all sizes regardless of how the seat is positioned. This arrangement allows them to place a **triggering mechanical sensor** on the sides of the seat cushions under the driver and front passenger. This prevents the air bag on the undamaged side of the car from inflating. Installing the entire air bag package in the seat-back also offers the advantage of preventing unnecessary deployments that might be caused by collisions with pedestrians or bicycles. It takes a collision of about **12 mph** (19 kph) to trigger side air bags.



BMW engineers have chosen **door-mounted air bags**. The door has more space, allowing for a bigger bag that provides more coverage.

Also under development is the [head air bag](#), or **Inflatable Tubular Structure (ITS)**, which was featured in all of BMW's 1999 models (except convertibles). The head bags look a little like big sausages and, unlike other air bags, are designed to stay inflated for about 5 seconds to offer protection against second or third impacts. Working with the side air bag, the ITS is supposed to offer better protection in some side collisions.

All of this makes it pretty clear that the science of air bags is still new and under rapid development. You can expect many advances in this field as designers come up with new ideas and learn from real-world crash data.

Crash Testing

Crash test dummies have been the subject of public service announcements, cartoons, parodies, even the name of a band. Real crash test dummies, however, are true life-savers as an integral part of automotive crash tests. Even though cars get a little safer each year, and fatality rates are declining, car crashes are still one of the leading causes of death and injury in the United States.



Photo courtesy [NHTSA](#)

One of the reasons cars have been getting safer is because of a well-established testing program.

Crash Test Dummies

The dummy's job is to simulate a human being during a crash, while collecting data that would not be possible to collect from a human occupant.



Photo courtesy [NHTSA](#)

All crash tests in the United States are conducted using the same type of dummy, the Hybrid III dummy. This guarantees consistent results. A dummy is built from materials that mimic the physiology of the human body. For example, it has a spine made from alternating layers of metal discs and rubber pads.

The dummies come in different sizes (click [here](#) to see some of the dummies), and they are referred to by percentile and gender. For example, the fiftieth-percentile male dummy represents the median sized male -- it is bigger than half the male population and smaller than the other half. This is the dummy most commonly used in crash testing. It weighs 172 lbs (78 kg) and is 69 inches (5 ft 9 inches or 1.75 m) tall.

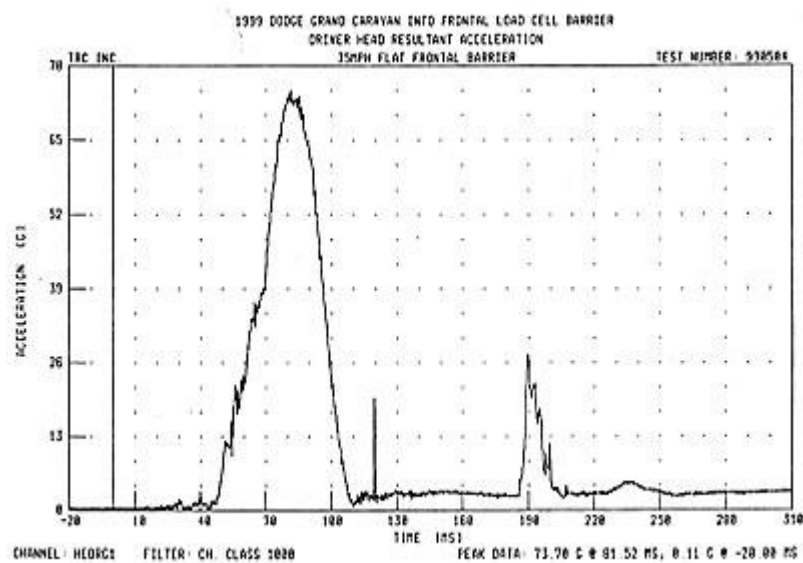
The dummies contain three types of instrumentation:

- Accelerometers
- Load sensors
- Motion sensors

Accelerometers

These devices measure the **acceleration in a particular direction**. This data can be used to determine the probability of injury. Acceleration is the rate at which speed changes. For example, if you bang your head into a brick wall, the speed of your head changes very quickly (which can hurt!). But, if you bang your head into a pillow, the speed of your head changes more slowly as the pillow crushes (and it doesn't hurt!).

The crash-test dummy has accelerometers all over it. Inside the dummy's head, there is an accelerometer that measures the acceleration in all three directions (fore-aft, up-down, left-right). There are also accelerometers in the chest, pelvis, legs, feet and other parts of the body.



A graph of the head acceleration during a crash test

The graph above shows the acceleration of the driver's head during a 35 mph (56.3 kph) frontal crash. Notice that it is not a steady value, but fluctuates up and down during the crash. This reflects the way the head slows down during a crash, with the highest values coming when the head strikes hard objects or the airbag.

Load

Sensors

Inside the dummy are load sensors that measure the amount of force on different body parts during a crash.

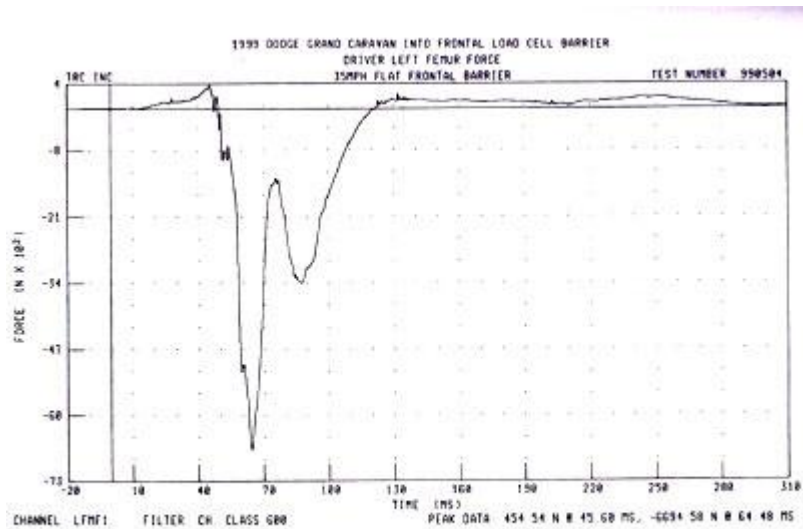


Photo courtesy

[NHTSA](#)

A graph of the force in the driver's femur during a crash

The graph above shows the force in Newtons in the driver's femur (the thigh bone), during a 35-mph frontal crash. The maximum load in the bone can be used to determine the probability of it breaking.

Movement

Sensors

These sensors are used in the dummy's chest. They measure how much the chest deflects during a crash.

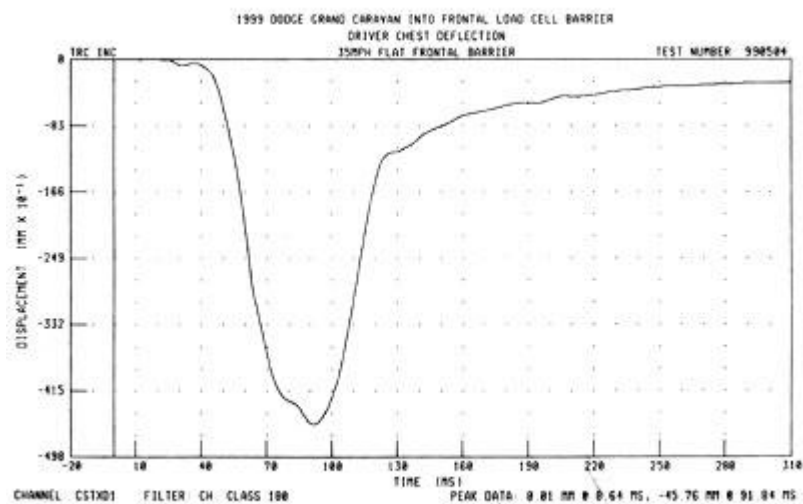


Photo courtesy

[NHTSA](#)

The chest deflection during a 35-mph frontal impact

The scan above shows the driver's chest deflection during a crash. In this particular crash, the driver's chest is compressed about 2 inches (46 mm). This injury would be painful, but probably not fatal.

Now let's take a look at a real crash test.

Crash Test

The [National Highway Traffic Safety Administration](#) (NHTSA) conducts two types of crash tests as part of the New Car Assessment Program.

- **35-mph frontal impact** - At 35 mph (56 kph), the car runs straight into a solid concrete barrier. This is equivalent to a car moving at 70 mph hitting a stationary car of the same weight.
- **35-mph side impact** - A 3,015-pound (1,368-kg) sled with a deformable "bumper" runs into the side of the test vehicle. The sled's tires are angled. The test simulates a car that is crossing an intersection being sideswiped by a car running a red light. The sled actually moves at 38.5 mph, but when you do the math, it is equivalent to a 35-mph side impact because of the way the wheels on the sled are angled.



Photo

courtesy

[NHTSA](#)

Click on this image for a video of an actual crash test.
(Video time: 2 min, 33 sec)

Crash Test Paint

Before the crash-test dummies are placed in the vehicle, researchers apply paint to them. Different colors of paint are applied to the parts of the dummies' bodies most likely to hit during a crash. The dummy's knees, face and areas of the skull are each painted with a different color. In the following photo, you can see that the blue paint from the dummy's face is smeared on the airbag and that his left knee (painted red) hit the steering column.



Photo courtesy [NHTSA](#)

The multicolored paint on the dummy shows where the different body parts hit the car.

If researchers note a particularly large acceleration in the data from the accelerometers in the dummy driver's head, the paint marks in the car will indicate what part of the body hit what part of the vehicle inside the cabin. This information helps researchers develop improvements to prevent that type of injury in future crashes.



Photo courtesy [NHTSA](#)

The front passenger-side dummy's knees hit the dashboard during the crash. Also, note that nothing from the engine compartment penetrated the cabin. The engine on most cars is mounted so that in a crash, it is forced backwards and downward so that it won't come into the cabin.

Now, let's take a look at a 35-mph frontal-impact test.

Vehicle Setup

The photo below shows a van that is ready to crash. The dummies have been placed in the car and are in position. All of the instrumentation on the car and dummies has been

hooked up and checked. Ballast is added to the car so that crash-test vehicle's weight -- and the distribution of that weight -- is equal to that of a fully loaded vehicle. A speed sensor has been mounted to the car and positioned so that it will pass through a pickup just as the car hits the barrier.



Photo

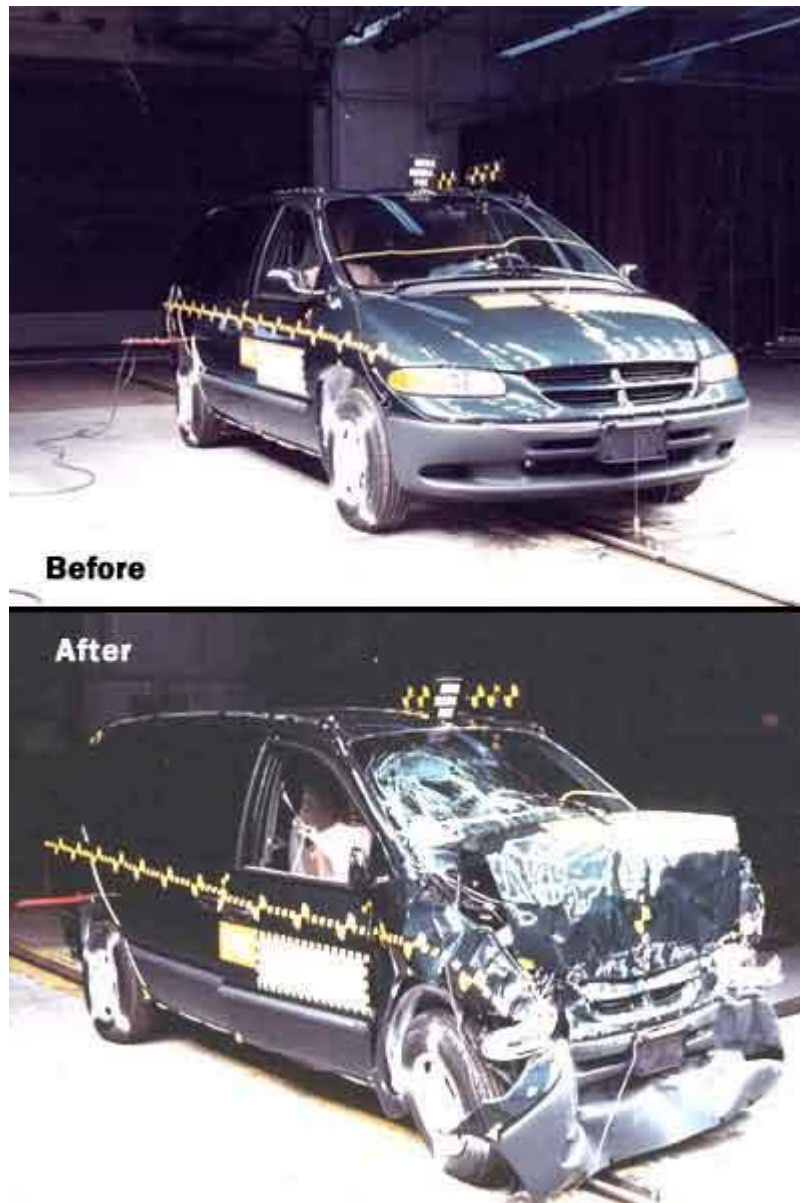
courtesy

[NHTSA](#)

A minivan in front of a barrier (note the camera's speed sensor)

There are 15 high-speed [cameras](#), including several under the car pointed upward. They shoot around 1,000 frames per second. Next, the car is backed away from the barrier and prepared to crash. A pulley, mounted in a track, pulls the car down the runway. The car hits the barrier at 35 mph. It only takes about 0.1 seconds from the time the car hits the barrier until it stops.

Let's take a look at some pictures. This car got four stars for both occupants in this frontal-crash test.



Photo

courtesy

[NHTSA](#)

The front of the same car, before and after the test

As you can see, the front of the car is completely crushed after the test. This is good, as the car has to get crushed and collapse in order to absorb the kinetic [energy](#) and stop the car.



Photo courtesy NHTSA

A better view of the front crushing

The front of the van is crushed up to the front wheels, which are pushed back. In this crash, the van actually got 23 inches (58 cm) shorter!

The "Perfect" Crash

Obviously, the ideal crash would be **no crash at all**. But, let's assume you are going to crash, and that you want the best possible chances of survival. How can all of the safety systems come together to give you the smoothest crash possible?

Surviving a crash is all about **kinetic energy**. When your body is moving at 35 mph (56 kph), it has a certain amount of kinetic [energy](#). After the crash, when you come to a complete stop, you will have zero kinetic energy. To minimize risk of injury, you would like to remove the kinetic energy as slowly and evenly as possible. Some of the safety systems in your car help do this.

Ideally, your car has seatbelt pretensioners and [force](#) limiters; they both tighten up the seatbelts very soon after your car hits the barrier, but before the airbag deploys. The seatbelt can then absorb some of your energy as you move forward towards the airbag. Milliseconds later, the force in the seatbelt holding you back would start to hurt you, so the force limiters kick in now, making sure the force in the seatbelts doesn't get too high.

Next, the airbag deploys and absorbs some more of your forward motion while protecting you from hitting anything hard.

In this hypothetical crash, the safety systems in the car all worked together to slow you down. If you didn't wear your seatbelt then the first stage of your protection is lost and it is going to hurt a lot more when you slam into the airbag. Many cars have seatbelt pretensioners and force limiters, but there are some even more exciting safety improvements coming.

Future Safety Improvements

It seems like [air bags](#) are sprouting from just about everywhere inside cars. And if they help keep your body from hitting hard objects during a collision, they're doing their job. But in the future, the emphasis on safety equipment will be to make it "smarter."

Eventually, we will see **smart airbags** that can deploy with different speeds and pressures, depending on the weight and seating position of the occupant, and also on the

intensity of the crash. We'll see **seatbelts** that will also sense the weight and position of occupants and adjust the tension and maximum [force](#) accordingly.

Technology is enabling carmakers to design and manufacture safer, smarter vehicles, and consumers clearly endorse this trend as reflected in buying patterns. It may take wrecking lots of cars and crash test dummies, but the information gained from automotive crash tests means you and your loved ones may survive an automobile accident with little or no injury.

Background and Ratings

In recent years, cars have gotten much safer. One reason is that safety is now a selling point in new cars -- people actually seek out and buy safer cars. In the United States, the NHTSA crashes cars and analyzes data with a goal of improving car safety.

Carmakers themselves crash many vehicles each year. Car manufacturers are required to certify that their cars meet the [Federal Motor Vehicle Safety Standards](#) (FMVSS). These rules cover everything from how bright the [turn signal](#) bulbs must be to the crash-testing requirements. Carmakers have to be certain that if the NHTSA goes to any dealer in the United States, buys any car and crashes it at 30 mph, the car will pass all of the FMVSS requirements. To ensure that all of the different combinations of [engines](#), [transmissions](#) and accessories will pass, carmakers might crash 60 to 100 vehicles themselves.

It is rare that a car fails the FMVSS requirements, so to challenge the carmakers even more -- and to provide valuable information to consumers buying cars -- the NHTSA started their **New Car Assessment Program** (NCAP). [NCAP](#) crashes cars at 35 mph (56 kph) in both frontal and side impact, and rates the cars based on how likely the occupants are to be injured during a crash. You can [find the ratings online](#), a good first stop when looking for a new car.

. A lot of research has been done (and is still being done) to classify injuries. Crash-test researchers came up with a standard called the **Abbreviated Injury Scale** (AIS) for classifying different injuries. These same researchers published a manual that contains detailed descriptions of all the injuries normally found in car crashes. Each injury is assigned a rank based on how severe it was: 1 is just minor cuts and bruises; 3 indicates a serious injury that requires immediate medical treatment and may be life threatening; 6 is fatal.

Rating

systems

Researchers have used crash test data to determine the likelihood of injuries that may be sustained in a crash. In addition, that data was used to create the NHTSA's star system. This system makes automobile safety ratings easier for consumers to understand when buying a car.

In **frontal crashes**, the star rating is determined by the worst score on these three criteria:

- **Head Injury Criteria (HIC)**
- **Chest deceleration**
- **Femur load**

In order to receive a five-star rating, all three of these criteria must be below the level that indicates a 10-percent chance of severe injury. There is a star rating for each of the front seat passengers, for each type of test that was run (frontal or side impact).

Ratings for Frontal-Impact Tests

# of Stars	Result
------------	--------

5	10% or lower chance of serious injury
4	11% to 20% chance of serious injury
3	21% to 35% chance of serious injury
2	36% to 45% chance of serious injury
1	46% or greater chance of serious injury

In **side-impact crashes**, there are two criteria:

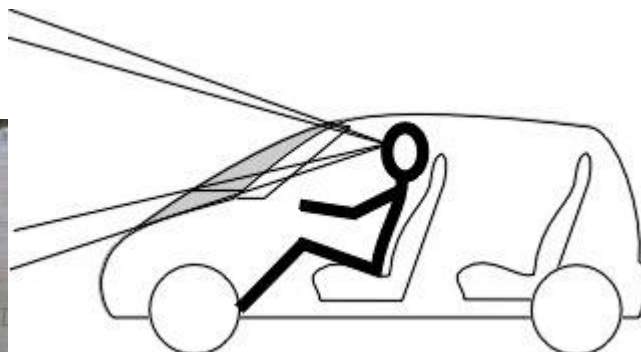
- **Thoracic Trauma Index (TTI)**
- **Lateral Pelvic Acceleration (LPA)**

To achieve a five-star rating in side-impact crashes, both criteria must be in the range that indicates less than a 5-percent chance of serious injury.

Ratings for Side-Impact Tests	
# of Stars	Result
5	5% or lower chance of serious injury
4	6% to 10% chance of serious injury
3	11% to 20% chance of serious injury
2	21% to 25% chance of serious injury
1	26% or greater chance of serious injury

Different Types of Body Structure

One-Box design



It is widely believed that one-box design offers the biggest interior space for a given external dimensions. However, I always doubt its effectiveness. Compare with conventional two-box hatchback, one box car frees up the space in front of the driver by pushing the windscreen forward. Nevertheless, as shown in the above drawing, such additional room (grey area) does not really contribute to driver's comfort. It just create a "freer" feel to the driver.

Because the windscreen is pushed forward, visibility is actually deteriorated, as shown in the drawing. The driver even cannot see the front end of his car, thus made arise some problems for parking.

Cab-foward design



Push the front-wheels towards the corners, shorten the engine compartment, move the windshield forward so that its base rests near the front wheels, this is the so-called "Cab-foward" design. Chrysler tells us Cab-foward design frees up the room for front passengers....



.... this is right when compare with long-nose traditional American cars



....but when compare with any standard European cars, Chrysler's cabin seems to be not so Forward.

Sandwich Structure - Mercedes A-Class



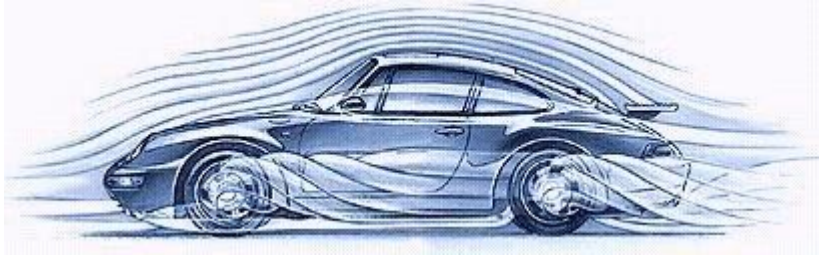
This structure is called "Sandwich" because the horizontal-orientated engine is placed above the floorpan but under the cabin. As a result, the cabin is raised by a massive 200 mm and so is the roof. What is the advantage of such structure ? Firstly, because of the disappearance of the front engine compartment, it made the car more compact than any other cars but simultaneously offers class-leading cabin space (actually runs close to C class).

Secondly, it provides exceptional crash-protection. Under crash, the engine will be pushed underneath the cabin instead of pushed towards the driver's legs as conventional cars. Therefore A class will pass any foreseeable crash test in the future. Thirdly, due to the inherent advantage in crash-protection, no additional crash structure is needed, thus a lot of weight is saved.

Aerodynamics

Drag and Lift

Drag

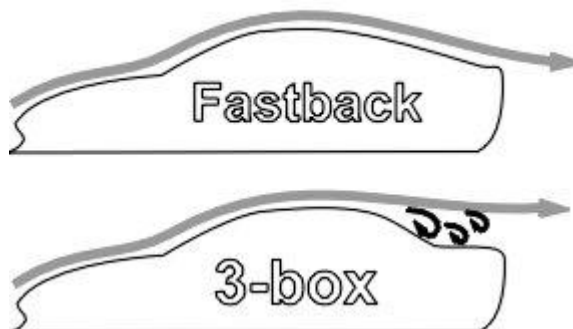


Aerodynamic efficiency of a car is determined by its Coefficient of Drag (C_d). Coefficient of drag is independent of area, it simply reflects the influence to aerodynamic drag by the shape of object. In theory, a circular flat plate has C_d 1.0, but after adding the turbulence effect around its edge, it becomes approximately 1.2. The most aerodynamic efficient shape is water drop, whose C_d is 0.05. However, we cannot make a car like this. A typical modern car is around 0.30.

Drag is proportional to the drag coefficient, frontal area and the square of vehicle speed. You can see a car travelling at 120 mph has to fight with 4 times the drag of a car travelling at 60 mph. You can also see the influence of drag to top speed. If we need to raise the top speed of Ferrari Testarossa from 180 mph to 200 mph like Lamborghini Diablo, without altering its shape, we need to raise its power from 390 hp to 535 hp. If we would rather spend time and money in wind tunnel research, decreasing its C_d from 0.36 to 0.29 can do the same thing.

Fastback

In the 60s, motor racing engineers started to take aerodynamics seriously. They discovered that if they reduce the slope of the back of a car to 20 degrees or less, the air flow will follow the roof line smoothly and dramatically reduce the drag. They termed this design as "Fastback". As a result, many racing cars, such as the Porsche 935 / 78 "Moby Dick" shown here, added an exaggeratedly long tail and lower the back.



For a 3-box car, air flow leaves the car straightly at the end of roof line. The dramatic drop of rear screen creates a low pressure area around, this attracts some air flows back to complement, thus creates turbulence. Turbulence always deteriorates drag coefficient.

However, this is still better than something between a 3-box and a fastback. If the rear screen angle is around 30 to 35 degrees, the air flow will be very unstable. It could greatly deteriorate the high speed stability. In the past, car makers had little knowledge about this and created many cars like this.

Lift

Another important aerodynamic factor is Lift. Since air flow above the car travels longer distance than air flow underneath the car, the former is faster than the latter. According to Bernoulli's Principle,

the speed difference will generate a net negative pressure acted on the upper surface, which we call "Lift".

Like drag, lift is proportional to area (but surface area instead of frontal area), the square of vehicle speed and Lift Coefficient (Cl), which is determined by the shape. At high speed, lift may be increased to such an extent that the car becomes very unstable. Lift is particularly serious at the rear, you can easily understand, since a low pressure area exists around the rear screen. If the rear lift is not adequately counter, rear wheels will become easy to slip, and that is very dangerous for a car travelling at something like 160 mph.

Fastback is particularly bad in this aspect, because it has a very big surface area in contact with air flow. It seems that good drag and good lift are mutually exclusive, you can't have both of them. However, as we did more research on aerodynamics, we found there are some solution to achieve both of them

Aerodynamic Aid

Wing (rear spoiler)

In the early 60s, Ferrari's engineers discovered that by adding an air foil (we simply call "Wing") to the rear end, lift can be dramatically reduced or even generates net downforce. At the same time, drag is only slightly increased.



The wing has the effect of directing the majority of air flow to leave the roof straightly without going to the back, this reduce lift. (If we increase the wing angle, a hundred kilograms of downforce may even be available.) There is still a little bit air flow follows the back and leave the tail under the wing. This avoid turbulence that appears in non-fastback car, thus remain drag-efficient. Since there is too little air follows this route, its contribution to the lift can be easily cancelled by the wing.



Wing must be installed high in order to be benefited from the majority air flow. Escort RS Cosworth is right Cougar, well, seems to use wing as decoration only.



The first wing car was Ferrari 246SP endurance racer in 1962. Just one year later, 250GTO road car incorporated a small duck tail rear wing, a first for road car of course. However, wing did not get popular until Porsche launched its 911 RS 2.7 in 1972, whose big duck tail reduced lift by 75% at high speed. Just one year later, 911 RS 3.0 used a "Whale tail" wing which completely eliminated lift. It became a trademark for the later 911s.

Porsche's new 996 Carrera offers us some useful data :

	Front lift (at 157mph)	Rear lift (at 157mph)
Wing down	64 kg	136 kg

Wing up	5 kg	14 kg
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Spoiler

Spoiler is the aerodynamic kit that alter underneath the car. We call those installed edge of front bumper as "Chin Spoiler" or those installed at the bottom edge of the "Skirt". To understand its principle, we about underside air flow.

Air flows underneath the car is always There are many components, such as gearbox, driving shaft, differential etc,

bottom of the car. They will obstruct the air flow, not only cause turbulence which increase drag, but also slow down the air flow thus increase lift. (Remember Bernoullis's Principle ?).

Spoiler is used to reduce underside air flow by encouraging air to pass either side of the car. As a result, drag and lift caused by underside air flow could be reduced. Generally speaking, the lower the spoiler locates, the better result obtain. Therefore you can see endurance racing cars having spoilers nearly touching the ground. Of course road cars cannot do so.



the air flows at the bottom "Air Dam", and car's sides as must first talk

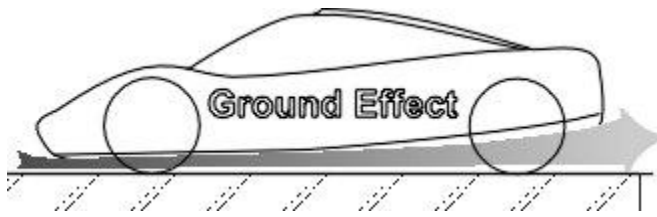
undesirable. engine, exposed in the

Smooth Undertray



We can also reduce the influence of underside airflow by covering the car's bottom by a smooth undertray, as shown in this Ferrari F355. This avoid turbulence and lift.

Ground Effect



To motor racing engineers, wing might be a good solution to lift, but still far away from what they really want. A typical formula one racing car corners at around 4g lateral acceleration, that requires substantial downforce to keep the tyres firmly on track. Install a huge wing with high angle can satisfy this requirement, but also deteriorates the drag coefficient.

In the 70s, Collin Chapman (again) invented a completely new concept to provide downforce without altering drag - Ground Effect. He incorporated an air channel into the bottom of his Lotus 72 racer. The channel is relatively narrow in front and expand towards the tail. Since the bottom is nearly touching the ground, the combination of channel and ground forms virtually a closed tunnel. When the car is running, air enters the tunnel in the nose and then expands linearly towards the tail. Apparently, air pressure is reducing towards the tail so that downforce will be generated.

Ground Effect is so superior than wing that it was soon banned in Formual One. In 1978, Brabham's Gordon Murray tried again with different means - instead of expansion channel, he used a powerful fan to create low pressure near the tail. Of course FIA banned it again.

Ground effect is not too suitable for road cars. It requires the bottom to be very close to the ground to form a closed tunnel. For racing car, this is no problem. But road cars should have much higher ground clearance to suit different rough roads, up hill and down hill etc. This greatly reduce the effectiveness of Ground Effect. McLaren F1 road car followed Brabham's trick by using 2 electric fans to create ground effect, but honestly speaking, no tester had ever praised its down force. Dauer 962, a so-called "road car" but it is actually a road-legal Porsche 962 endurance racing car, use conventional air-channel ground effect as the race car. Adjustable ride height allow it to run in rough road (slowly) and make good use of Ground Effect in Germany's Autobahn. Nevertheless, it can barely generate 40% downforce of the racing car.

Cd World Record

Cd	Year	Model	Remark
0.137	1986	Ford Probe V	Concept car
0.19	1996	GM EV1	Electric car
0.25	1999	Honda Insight	Hybrid car
0.25	2000	Lexus LS430	--
0.25	2000	Audi A2 "3-litre"	--
0.26	1989	Opel Calibra	2.0i base model
0.26	2000	Mercedes C180	--
0.27	1996	Mercedes E230	--
0.27	1997	VW Passat	--
0.27	1997	Lexus LS400	--
0.27	1998	BMW 318i	--
0.27	2000	Mercedes C-class	C200 up to C320