Handbook of Vehicle and Automobile Engine Technologies

Shaun Tyler

Salvatore Cortez

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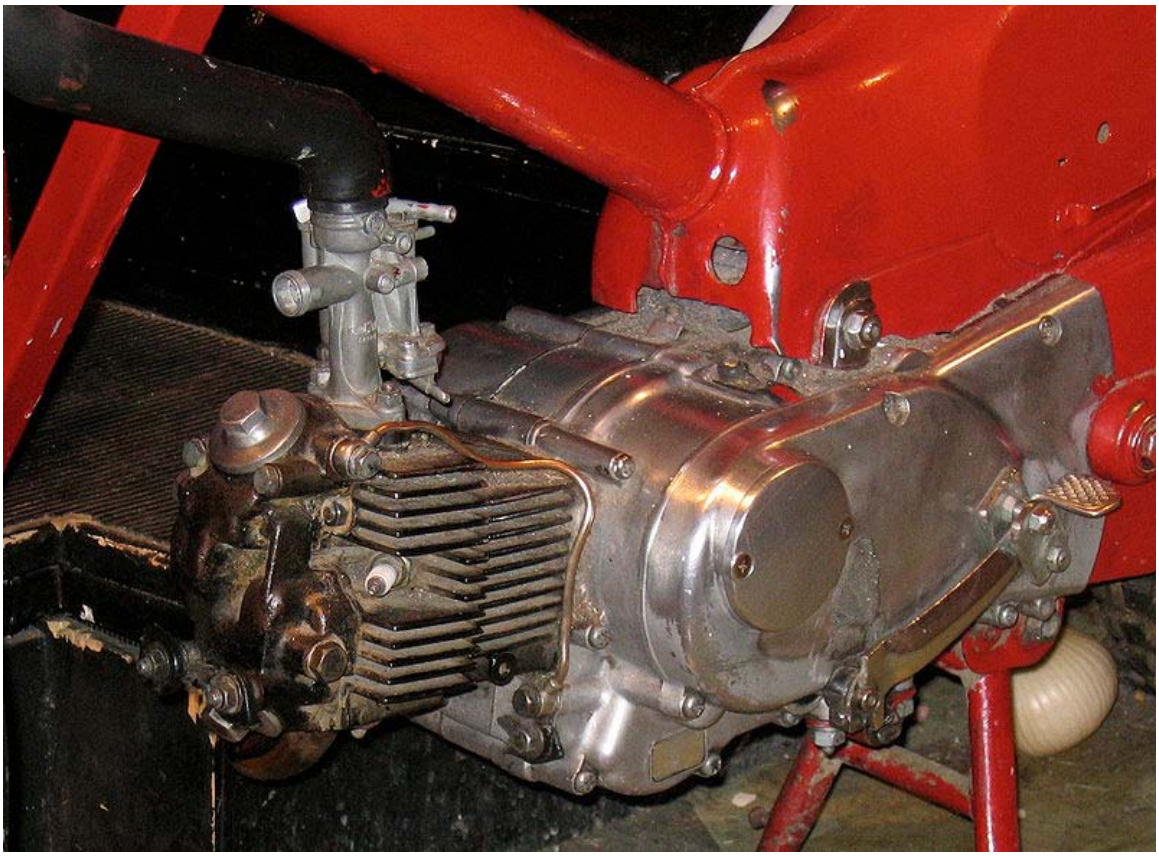
Chapter 1

Motorcycle Engine



A Honda Super Cub engine. This 50 cc (3.1 cu in) horizontal single powers the most popular motorcycle in history, with over 60 million produced.

A **motorcycle engine** drives the rear wheel of a motorcycle and powers forward motion. Motorcycle engines vary in cylinder quantity, head design, displacement and layout.

Some motorcycle manufacturers have become strongly associated with one particular engine configuration. Modern Harley-Davidson motorcycles are exclusively transverse, narrow-angled V-twin engines, while Ducati and Moto Guzzi have specialised in 90° V-

twins, the former transverse and the latter longitudinal with shaft drive. Longitudinal boxer twins are iconic of BMW motorcycles, although they now use a number of different engine layouts. British marques of the 1950s and 1960s were associated with parallel-twins even though they made other types as well. Japanese manufacturers vary greatly in layouts, and Honda in particular have produced almost every possible configuration and type.

History

Earliest motorcycle engine concept. This 1818 caricature was thought for many years to be entirely fanciful, until the Michaux-Perreaux, Roper and other steam cycles were rescued from obscurity, and the stories of the early steam cycle experiments were rediscovered. There were no steam motorcycles in 1818, but there soon would be.

The first motorcycles were powered by steam engines. The earliest example is the French Michaux-Perreaux steam velocipede of 1868. This was followed by the American Roper steam velocipede of 1869, and a number of other steam powered two and three wheelers, manufactured and sold to the public on through the early 20th century.

Using frames based both on the earlier boneshaker and the later—and in many ways completely modern—safety bicycle design, these early steam motorcycles experimented with a variety of engine placement strategies, as well as transmission and options. While today nearly every motorcycle has its engine in the center of the frame, this became standard only around 1900-1910 after nearly every possible engine location was tried.

The modern scooter engine arrangement was arrived at in the 1940s and remains the same today.

The Otto cycle gasoline internal combustion engine was first used on an experimental two wheeler created by Gottlieb Daimler to test the practicality of such an engine in a vehicle. This motorcycle, the Daimler Reitwagen, is credited as the *world's first motorcycle* by many authorities, partially on the assumption that a motorcycle is defined not as any two wheel motor vehicle, but a two wheel *internal combustion engine* motor vehicle. The Oxford English Dictionary, for example, defines the word motorcycle this way. The steam cycles were also simply neglected and forgotten by many historians, even as the Michaux-Perreaux waited forty years on display in the National Motor Museum, Beaulieu.

In recent years, a surge in interest in clean energy has put many new electric powered two wheelers on the market, and they are registered as motorcycles or scooters, without the type of powerplant being an issue. Diesel motorcycles were also been experimented with briefly throughout the 20th century, and are again the subject of interest due to fuel economy and the needs of military logistics. The USMC has ordered a new diesel motorcycle, the M1030 M1, that can use the same fuel, JP-8, as the rest of their armored vehicles, aircraft, cars and trucks.

The overwhelming majority of the motorcycles produced and used in the world today have small displacement air-cooled single-cylinder engines, both two- and four-strokes. In the wealthier parts of the world, Europe and Japan, larger displacements and multiple cylinders are common alongside small-displacement bikes required by various licensing and rider experience requirements, and so a very diverse range of sizes, cylinder numbers, configurations, and cooling systems are seen on the road. Many developed countries have graduated licensing, where a rider is licensed for a period of time to ride only smaller-displacement motorcycles before being allowed to ride larger ones. In the United States, there are no such mandates, and so the mix is skewed even further to the largest displacements, consumer demand drives manufacturers to offer their largest motorcycles to that country, and to export far fewer sub-600 cc (37 cu in) models to the American market.

Types

Almost all commercially available motorcycles are driven by conventional gasoline internal combustion engines, increasingly four-strokes in all size ranges. Some are still air-cooled (forced with a fan in some cases) but water-cooling is more common. The mid-range and large two-strokes seen in the 1970s and 1980s have almost disappeared, particularly as emission laws were introduced. There are a few small scooter-type models using batteries and an electric motor. Van Veen, Hercules, Norton, and Suzuki produced quite small numbers of motorcycles propelled by Wankel rotary engines. The 2009 TT races included a new category 'TTX' for electric bikes using either fuel-cells or batteries

Most motorcycle engines have the primary working member or crankshaft across the frame (transverse mounting). Others are arranged to turn a shaft-drive to the rear wheel and the crankshaft is longitudinal, along the frame.

A sub-type of motorcycle, the scooter, has the engine as part of the rear suspension, so it is not fixed to the main frame. Such engines pivot to follow the road surface and are partly "unsprung weight". The final drive of scooters is much shorter than that of regular motorcycles and is contained within the engine casings in an oil-bath, a design that is only suitable for machines with small wheels, or is fully automatic using belts and expanding/contracting pulleys, ala DAF variomatic cars. The engines of the motorcycles known as underbones or "step-throughs" may be of either kind.

Two-stroke and four-stroke

Two-stroke engines have fewer moving parts than four-stroke engines, and produce twice the number of power strokes; consequently, two-stroke engines are more powerful for their mass. Two-strokes offer stronger acceleration, but similar top speed compared to a four-stroke engine. They are also easier to start. However, two-stroke engines have shorter life due to poorer piston lubrication, since lubrication comes from the fuel-oil mix.

Four-stroke engines are generally associated with a wider power band making for somewhat gentler power delivery, but technology such as reed valves and exhaust power-valve systems has improved ride-ability on two-strokes. Fuel economy is also better in four-strokes due to more complete combustion of the intake charge in four-stroke engines.

Nevertheless, two-strokes have been largely replaced on motorcycles in developed nations due to their environmental disadvantages. Cylinder lubrication is necessarily total-loss and this inevitably leads to a smokey exhaust, particularly on wide throttle openings. Two-stroke engined motorcycles continue to be made in large numbers, but mostly low power mopeds, small scooters and step-through underbones where they still compete strongly with four-strokes (including the highest selling motorcycle of all time, the 50 cc Honda Super Cub). The major markets of two-stroke motorcycles are in developing nations.

Heads

Motorcycle engine heads are the subject of a great deal of attention, due both to the critical role played by intake, exhaust and valve systems in the overall efficiency of an engine, but also because on a motorcycle the head is often the center of attention, aesthetically speaking. Harley-Davidsons, Moto Guzzis and BMWs are categorized by their heads, such as airhead, panhead, oilhead, and even knucklehead. The eras of Ducati production, and the camps or factions their enthusiasts gather in, are divided by head, whether they be pushrod, bevel heads, desmos, or chain- or belt-driven valves.

Valve control

Honda equipped the CBR400F with HYPER VTEC (or REV:Revolution-modulated valve control) in 1983. The system enabled to switch over the number of valve operations per cylinder between low and medium speed revolution range and high speed revolution range. In January 2002 HYPER VTEC evolved into Spec II and in December 2003 SPEC III was introduced.

Unit construction

Engines and gear-boxes were originally quite separate, with drive from one to the other by a chain (the 'primary'). Gradually these components were moved closer and closer together until they were eventually incorporated in the same case (actually, 2 compartments in one case).

Displacement

Engine displacement is defined as the total volume of air/fuel mixture an engine can draw in during one complete engine cycle. In a piston engine, this is the volume that is swept as the pistons are moved from top dead center to bottom dead center. This is the "size" of the engine. Motorcycle engines range from less than 50 cc, commonly found in many mopeds and small scooters, to a 6,000 cc engine used by Boss Hoss in its cruiser style motorcycle BHC-3 LS2. Many state laws in the U.S. define a motorcycle as having an engine larger than 50 cc, and a moped as a vehicle with an engine smaller than 60 cc.

Cylinders and configuration

Small motorcycles normally have a single cylinder, many smaller and mid-range motorcycles have twin cylinders and most medium to large motorcycles have four cylinders. However, no generalizations can be made, as there are a few large singles and twins. Three cylinders have been widely used and there have been some six-cylinder machines. Many different layouts have been used with vertical cylinders the most popular. There are some horizontally opposed and V layouts.

Single

1960 BSA Gold Star

Single cylinder engines (known as "singles" or occasionally "thumpers") may have the cylinder vertical or horizontal, the latter particularly common in step-through or underbone motorcycles. Single cylinder engines require a larger flywheel, hindering ultimate performance but are a lot easier to maintain in almost every respect. In road motorcycles, single-cylinders tend to be associated with cheaper, utility motorcycles for daily transport. These motorcycle engines are tuned to give more power at lower engine revolutions, improving control, safety and engine longevity.

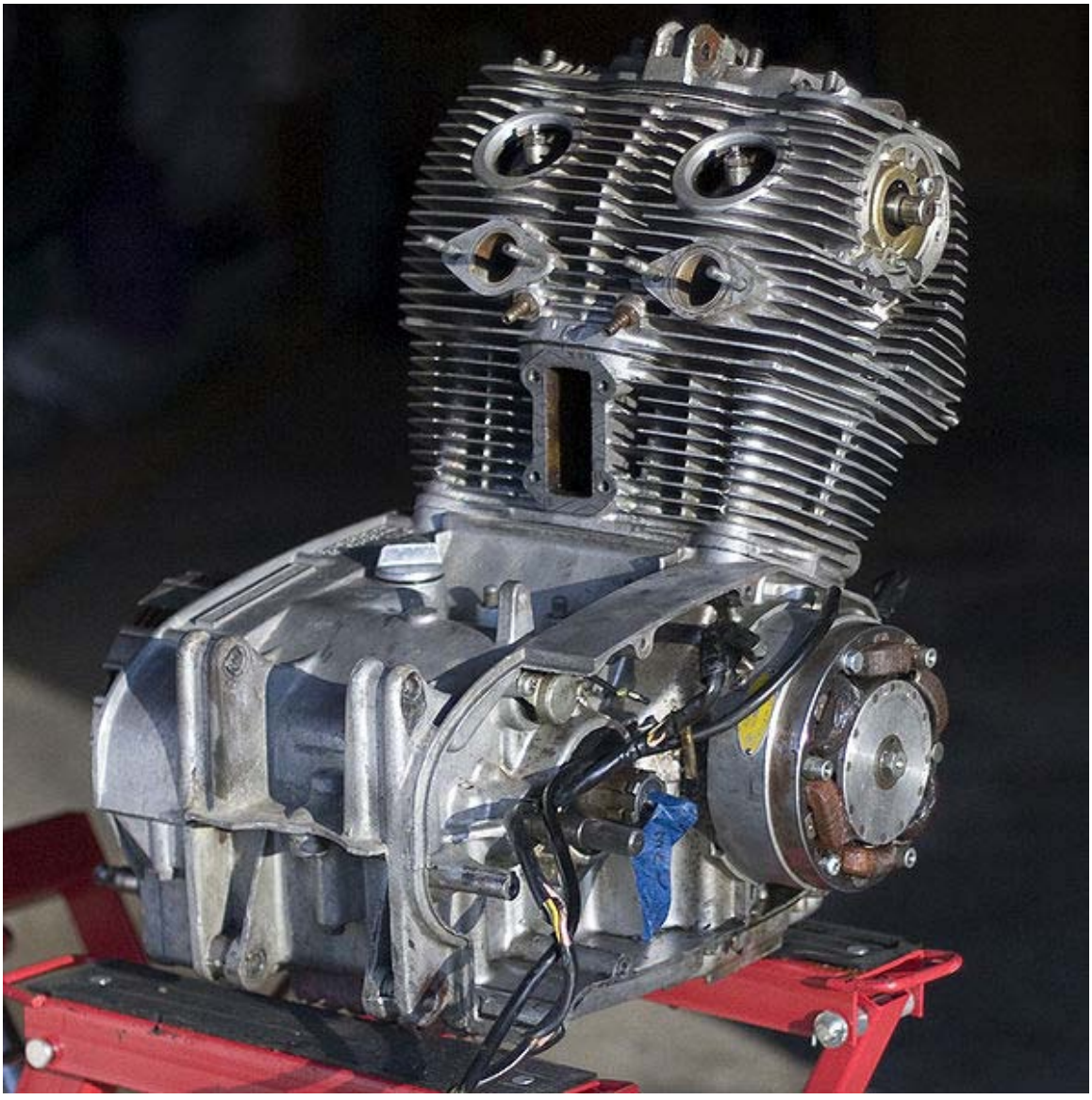
The need for the flywheel effect is less pronounced in all forms of competition motorcycles since they spend almost no time at tick-over speeds, all through the 1950s many of the fastest road racing motorcycles such as the Manx Norton were single-

cylindered. The reduced weight and narrow width of single-cylinder motorcycles continue to make the layout well suited for the great majority of off road motorcycles, including those in top competition.

Split Single (a radical form of two-stroke) were used very successfully by DKW and Puch between and after the wars, losing out only to the loop-scavenging Japanese twin and triple machines of the 1970s.

Twin

Parallel-twin



1962 Honda CB77 Superhawk 305 cc (18.6 cu in) twin engine.

Two-cylinder engines are known as twins. The parallel twin as in most common British and many Japanese motorcycles. Engines of this design typically have the cylinders side

by side vertically above the crankcase, with the exhaust ports pointing forward to maximize airflow cooling. Longitudinal twins include the 500 cc Sunbeam S7 and S8. The two crankpins can be timed simultaneously, with each side firing alternately every 360° (most British bikes), or timed with 1 piston at TDC and the other at BDC to fire 180° apart, followed by a long "dead" interval (many Hondas). Some Hondas have been made with both crankshaft types. Some engines, such as the Matchless 650, have had a 3rd center main bearing between the crankpins, but this was not successful.

The parallel-twin engine configuration was made famous by Edward Turner's Triumph Speed Twin design as used on the Bonneville 20 years later.

V-twin

Harley-Davidson Sportster V-twin

The V-twin engine where the cylinders form a "V" around the crankshaft, which is oriented longitudinally with the cylinders protruding left and right on models such as on the Honda CX500 and most Moto Guzzi motorcycles, or more typically transversely . V-twins can also be separated into three types, one having a shared crankpin (a normal con-rod is inserted between a forked con-rod thus sharing the single crankpin and keeping the cylinders in line, a single crankpin with side-by-side connecting rods and offset cylinders, or two crankpins, with the cylinders offset, which nearly every one else uses.

The angle in the V-twins varies from around 42° (Indian), 45° (Harley-Davidson), 60°, and up to 90°. Typical of the former are the Harley-Davidson and Vincent engines which because of their firing order tend to vibrate more. Ducati and Moto Guzzi make V-twins with cylinders arranged at a 90 degree angle to quell primary vibrations.

Flat twin

BMW's opposed twin

The opposed twin engine's cylinders normally protrude sideways into the cooling air stream, although some early motorcycles had them transversely mounted.

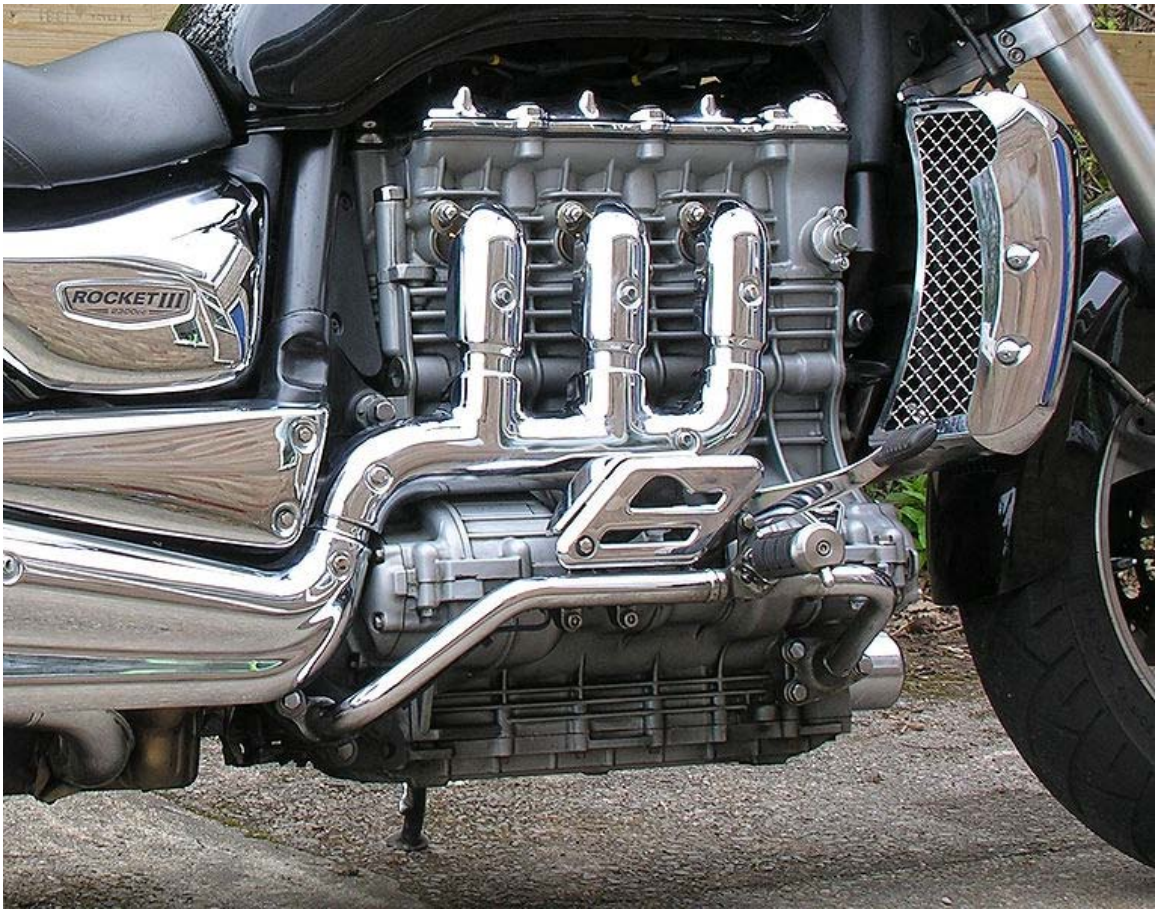
In the flat-twin (boxer) engine, which is used by BMW Motorrad, Ural, Harley-Davidson's WW2 "XA" model, Marusho, and historically by Douglas, the cylinders are horizontally opposed, protruding from either side of the frame. The boxer is the only twin-cylinder arrangement that has inherent primary balance without a rocking couple, producing very low vibration levels without the use of counterbalance shafts.

Tandem twin

The Tandem Twin where the cylinders are longitudinal, and have two cranks geared together such as Kawasaki's KR250 road bike and KR250 and KR350 GP Bikes.

Triple

Inline 3



Triumph Rocket III inline-3

Three-cylinder designs are referred to as "triples" and are normally inline triples in layout. The British Hinckley-built Triumph, mostly transverse but also the 2,300 cc longitudinal Rocket III, Italian Benelli and Japanese Yamaha XS750 are three motorcycle manufacturers who have used triples in their large displacement motorcycles. The Italian firm Laverda made a few 1,000 cc and 1,200 cc triples. BMW made the K75 longitudinal 750 cc triple with the cylinders parallel to the ground. BSA made the Rocket-3 transverse 750 cc and old Triumph the 750 cc Trident

Two-stroke triples were somewhat more common historically. The Kawasaki triples were produced with capacities of 250, 350, 400, 500, and 750 cc in the 1970s, while Suzuki produced 380, 550, and 750 triples (the last being water cooled). Motobecane made 350 cc and fuel injected 500 cc triples with 3 into 4 pipes in the early seventies. Honda produced the water cooled V-3 two-strokes MVX250 and NS400. There have been various race bike triples such as Kawasaki KR750, Suzuki TR750 transverse 3's, and Proton/Modenas KR3, Honda NS500 V-3s.

Four

Four-cylinder engines are most commonly found in a transverse-mounted inline four layout, although some are longitudinal (as in the earlier BMW K100). V-4 and boxer designs (as in the earlier Honda Gold Wing) have been produced. One of the more unusual designs was the Ariel Square Four, effectively two parallel-twin engines one in front of the other in a common crankcase – it had remarkably little vibration due to the contra-rotating crankshafts.

Inline 4

Honda CB750 transverse inline-4

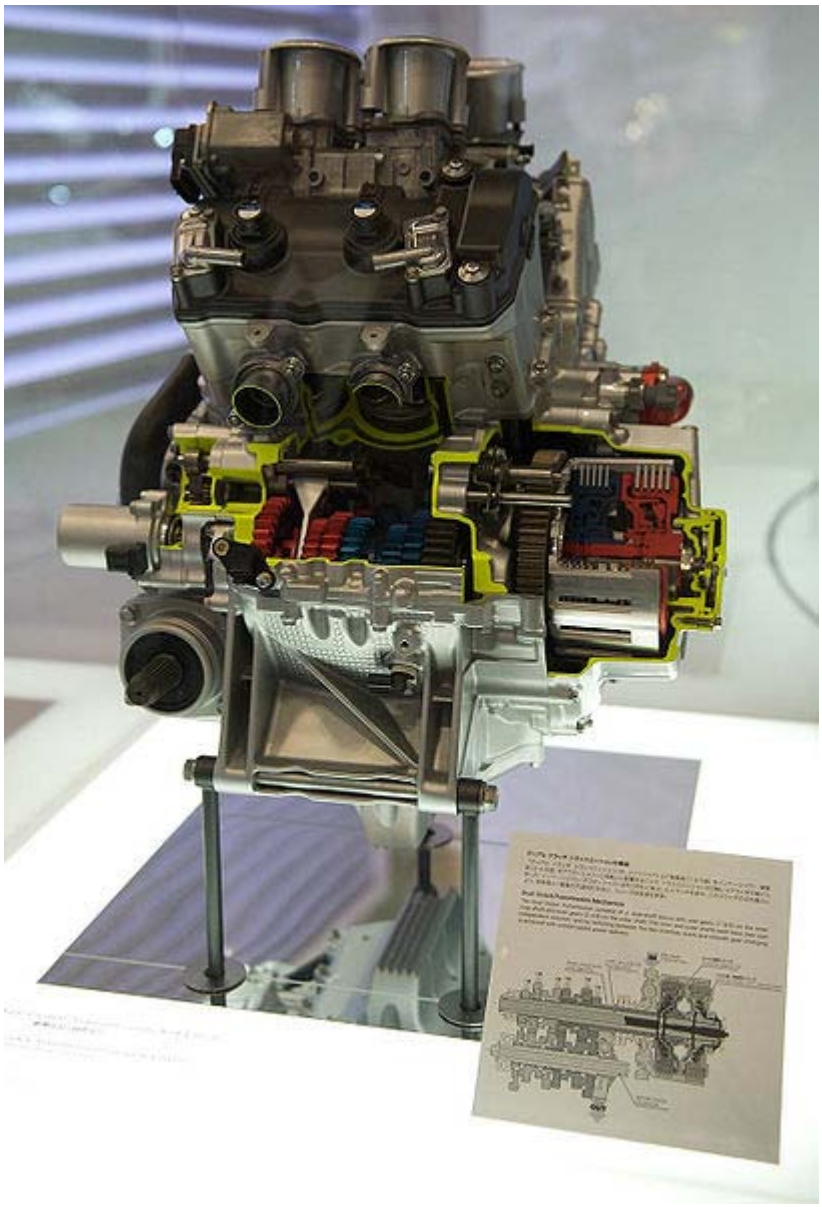
Since the advent of the Honda CB750 straight-four engine, straight-fours have dominated the non-cruiser street motorcycle segments. The German manufacturer Münch based their

motorcycles on four cylinder car engines (e.g. Mammut 2000 has a 2.0l with a turbo and cylinder heads by Cosworth).

Flat 4

The Honda GL1000 flat-four

V4



Honda VFR1200F engine with dual clutch transmission.

Honda uses V4 engines in the ST series and VFR series. As for two-stroke engines, there were four cylinders in the smaller classes such as Kawasaki's 125 cc KR3 square 4 and Yamaha's 250 cc RD500 V4 (RZ 500 in the US). Yamaha later raced transverse four TZ500/700/750's and virtually all the bikes in the last decade of the two-stroke GP500 era were fours (first squares then Vees) i.e. Honda, Kawasaki, Cagiva, Suzuki, Yamaha - Kawasaki also experimented with a trapezoidal four the 602S. Yamaha made the V4 RD500LC, and Suzuki the RG400 and RG500 square four road bikes.

Square 4

A square four is a U engine with two cylinders on each side. This configuration was used on the Ariel Square Four motorcycle from 1931 to 1959. This design was revived as a two-stroke version on some racing Suzuki models, and their subsequent road-going version the RG500. Although some racing success was achieved, the road bikes didn't sell in great numbers, and the design was phased out in favour of in-line, four-stroke designs, as at the time two stroke engines were quickly being superseded by more economical, reliable, and emissions-friendly four-strokes.

Five

V5

Honda V5 MotoGP engine

Honda has produced five-cylinder engines for racing, the RC211V 990 cc V5. No V5 engines are currently available in commercial production motorcycles.

Six

Inline 6

Benelli Sei inline-6

Six-cylinder engines are rare and found only on the biggest motorcycles. Two easily recognizable examples in recent times have been the Honda CBX and the Kawasaki KZ1300 and also Kawasakis Voyager XIII, Bennelli also made 750 cc and 900 cc Straight sixes known as the Sei. Honda made a 250 cc straight-six GP bike. Modern straight-six motorcycles include the BMW K1600GT and K1600GTL, which have a transverse-mounted 1,649 cc engine.

Flat 6

Honda Valkyrie flat-6

The six-cylinder engine is currently used by Honda in the boxer engine of the Rune, Valkyrie and Gold Wing.

V8

Moto Guzzi V8

Galbusera built a V8 in 1938, and Moto Guzzi experimented over a period of two years with its dual overhead cam 500 cc V8 (the Otto Cylindri) in the 1950s. Some custom and one-off motorcycles use more than six cylinders. For example, the Boss Hoss motorcycle uses (5,700 cc, 6,000 cc and 8,200 cc) Chevy V-8 crate motors. In the 1990s Daimler-Chrysler manufactured a limited number of Tomahawk concept bikes featuring a Dodge Viper's V-10 engine. Australian company Drysdale have built short runs of 750 cc V8 superbikes and 1L V8 roadgoing motorcycles, both with engines specifically developed for the purpose. No major motorcycle manufacturer has used eight or more cylinders although Honda made the 'almost' V8 oval piston NR750 road bike and NR500 GP bike (having eight connecting rods, for example) and Morbidelli has shown two V8 prototype road bikes, but has yet to get off the ground

Other types

Wankel rotary

Hercules (motorcycle), Norton Commando, ZF Sachs, Suzuki RE5

Oval pistons

Honda NR

Rotary engines

Megola, Killinger and Freund Motorcycle

Jet engines

MTT Turbine Superbike

Diesel

Only very small numbers of diesel engined motorcycles have ever been built. The improved fuel efficiency is offset by the increased weight, reduced acceleration and potential difficulty of starting, at least in colder climates. Enfield India built a few from 1965 onwards but is no longer doing so. In November 2006, the Dutch company E.V.A. Products BV Holland announced their first diesel-powered motorcycle, its Track T-800CDI, using an 800 cc three-cylinder Daimler Chrysler diesel engine.

Several armies are moving to an all-diesel engine fleet to reduce the fire risks of petrol and the need to provide two different fuels. This includes their despatch riders as well, encouraging the market for diesel motorcycles. Interest in biofuels is also likely to encourage future developments for small Diesels.

Diesels are also available in both two and four-stroke versions.

Engine cooling

Liquid

Liquid-cooled motorcycles have a radiator (similar to the radiator on a car) which is the primary way their heat is dispersed. Coolant is constantly circulated between this radiator and the cylinders when the engine is running. While most off-road motorcycles have no radiator fan and rely on air flowing over the radiators from the forward motion of the motorcycle, many road motorcycles have a small fan attached to the radiator which is controlled by a thermostat. Some off-road motorcycles are liquid cooled and anti-dirt protection is attached to the radiator. The cooling effect of this fan is enough to prevent the engine overheating in most conditions, so liquid-cooled bikes are safe to use in a city, where traffic may frequently be at a standstill.

Emissions regulations and the market demand for maximum power are driving the motorcycle industry to liquid-cooling for most motorcycles. Even Harley-Davidson, a strong advocate of air-cooled motors, has begun producing a Revolution liquid-cooled engine.

Air

Most air cooled motorcycles take advantage of air blowing past the cylinder and cylinder head while in motion to disperse heat. Frequent, sustained stationary periods may cause over-heating. Some models (mostly scooters) are equipped with fans that force the air to go past the cylinder block, which solves the problem of city driving. The cylinders on air cooled bikes are designed with fins (heat sinks) to aid in this process. Air cooled bikes are cheaper, simpler and lighter than their water-cooled counterparts.

Oil

The BMW R1150GS has an oil cooler below the headlights and fins for air cooling on the cylinders

Some manufacturers use a hybrid cooling method where engine oil is circulated between the engine case and a small radiator. Here the oil doubles as cooling liquid, prompting the name "oil-cooling." Suzuki has produced many "oil-cooled" motorcycles. Modern BMW R-series flat-twin motorcycles, such as the R1150GS, use air and oil cooling. Polaris's Victory motorcycles use oil/air cooling exclusively.

Other components

Fuel injection and computer engine management systems are now normal on middle range and larger motorcycles and are increasingly being incorporated onto the smaller machines, partly driven by better emission control and lower maintenance but mostly by manufacturing cost considerations. Ignition systems moved from magneto in the 1950s to battery-coil-contact breaker (points), and these were increasingly superseded by Capacitor Discharge Ignition (CDI) from the 1980s. Small, single cylinder motorcycles abandoned the flywheel magneto system with contact breakers to similar flywheel driven solid-state systems at about the same time.

Turbo and Superchargers. Superchargers (blowers) were common in the GP's, until they were banned (which didn't help the two-stokes, as pre Ernest Degners new technology, they needed the help against the four-strokes). The big four also made a turbo-ed bike, Honda made two....., mainly as an exercise in technical expertise and later discontinued for more conventional methods. Bolt on (well nearly) blowers are available to put on street bikes - and they are essential for drag bikes and land speed record streamliners etc. Most sports bikes now use some sort of 'ram-air' system where, as road speed increases, more and more air is forced through ducts in the fairing to pressurize the airbox.

Chapter 2

Big-Bang Firing Order

A **big bang engine** is an unconventional motorcycle engine designed so that most of the power strokes occur simultaneously or in close succession. This is achieved by changing the ignition timing; sometimes in combination with a change in crankpin angle. The goal is to change the power delivery characteristics of the engine or exhaust sound. A regular firing multi-cylinder engine fires at approximately even intervals, giving a smooth-running engine. Because of a big bang engine's power delivery imbalance, there exists more vibration and stress in the engine. This imbalance can overwhelm the rear tire, and generally makes a slide harder to catch. Until recently, this has limited their use to racing.

Twins and twingles

Engine	Crankshaft	Ignition timing	Graphical	Example
Single (2-stroke) Parallel twin Flat twin	360° 180°	360-360	1-0-0-0-1-0-0-0-	BSA, Triumph, Norton, AJS, Matchless and BMW F800S BMW R series
Single Parallel twingle Flat twingle	360° 180°	720	1-0-0-0-0-0-0-0- 2-0-0-0-0-0-0-0- 2-0-0-0-0-0-0-0-	
Parallel twin	180°	180-540	1-0-1-0-0-0-0-0-	1966 Honda “Black Bomber”, Yamaha TX500 and Kawasaki ER-6
Parallel twin 90° V twin	270° 360°	270-450	1-0-0-1-0-0-0-0-	Yamaha TRX850 and Triumph Thunderbird 1600 Ducati
45° V twin	360°	315-405	1-0-0-010-0-0-0-	Harley-Davidson
45° V	360°	45-675	110-0-0-0-0-	Modified Harley-Davidson XR-750

twingle	0-0-	for flat track racing	

Parallel twins

The classic British parallel twins (BSA, Triumph, Norton, AJS & Matchless) had a 360° crankshaft that, compared to a single, gave twice as many ignition pulses, which were evenly spaced.

The early Japanese parallel twins, like the 1966 Honda “Black Bomber” and Yamaha TX500, adopted a 180° crank that gave an uneven firing pattern. This configuration has the best possible primary mechanical engine balance for a parallel twin; the uneven firing was a by-product of this design.

The Yamaha TRX850 had a 270° crank that allowed a more regular firing pattern than a 180° crank, and less regular than a 360° crank. This configuration has the best possible secondary engine balance for a parallel twin; its exhaust sound and power delivery is identical to a 90° V-twin.

Twingles

A twingle is a two-stroke twin cylinder engine with an altered firing order designed to give power pulses similar to a single cylinder four-stroke engine. It is well known that four-stroke singles "hook up" better than two-strokes in the dirt. This is because four-strokes have half as many power strokes per crankshaft revolutions as a two-stroke. This creates a recovery gap during which the rear tire regains traction.

Inline twins with a 360° crankpin offset and flat-twins can be easily converted into twingles by firing both of the cylinders at the same time. The Vintage Dirt Track Racing Association (VDTRA) 2010 Rules have banned vintage motorcycles from being setup as a twingle.

V twins

A narrow angle v-twin such as the 45° Harley-Davidson naturally has slightly uneven spaced power strokes. By changing the ignition timing on one of the cylinders by 360° the power strokes are very closely spaced. This will cause uneven fuel distribution in an engine with a single carburettor. The Harley-Davidson XR-750 with twin carburettors was a popular bike to twingle. It had great success in flattrack racing.

Four cylinder engines

Engine	Crankshaft	Ignition timing	Graphical	Example
I4	180°	180-180-180-180	1-0-1-0-1-0-1-0-	Honda CB750
I4 'Long bang'	180°	180-540	2-0-2-0-0-0-	Shinya Nakano's

			0-0-	Kawasaki Ninja ZX-RR
I4 'Uneven bang'	crossplane	180-90-180-270	1-0-1-1-0-1-0-0-	2009 Yamaha YZF-R1
70° V4 90° V4	180°	180-70-180-290 180-90-180-270	1-0-1-1-0-1-0-0-	1985-2007 Yamaha V-Max Honda VFR800
90° V4 'Twin pulse'	70°	90-200-90-340	1-1-0-1-1-0-0-0-	Ducati Desmosedici RR
90° V4 'Droner'	360°	90-270-90-270	1-1-0-0-1-1-0-0-	Honda VF/RC30/RC45
112° V4 'Big bang' (2-stroke)	180°	68-292-68-292	2-2-0-0-2-2-0-0-	1990 Honda NSR500
90° V4 'Screamer' (2-stroke)	180°	90-90-90-90-90-90-90-90	1-1-1-1-1-1-1-1-	1984 Honda NSR500

Inline fours

A four-cylinder engine with a regular firing interval is sometimes referred to as a screamer. The regular delivery of power strokes can overwhelm the rear tire, and generally makes a slide harder to catch as well. A long bang fires both pairs of cylinders in quick succession; the power delivery is identical to a parallel twin with a 180° crank and similar to a v-twin. In 2005 Kawasaki experimented with this configuration on the ZX-RR MotoGP bike.

The 2009 Yamaha YZF-R1 has instead an uneven firing order. The power delivery is the same as a 90° V4 with a 180° crank, such as the Honda VFR800 and very similar to the Yamaha V-Max which has been lauded for its exhaust sound.

2-stroke V4

The Honda NSR500 began and ended its life as a screamer. However in 1990 Honda connected both of the pistons in one bank to the same crankpin and both of the other pistons to a crankpin offset 180°. This NSR500 was called a 'big bang'. Yamaha created a big bang YZR500 in 1992. The YZR500 had two crankshafts like a U engine and the angle between each pair of cylinders was 90°, like a V4.

In 1997 Mick Doohan wanted to run a 180° screamer engine. HRC crew chief Jerry Burgess explains why: "The 180 got back a direct relationship between the throttle and the rear wheel, When the tire spun I could roll off without losing drive. The big bang has a lot of engine braking, so it upsets the bike into corners, then when you open the throttle you get this sudden pulse of power, which again upsets the suspension. Mick's secret is corner speed, so he needs the bike to be smooth and the 180 is much smoother."

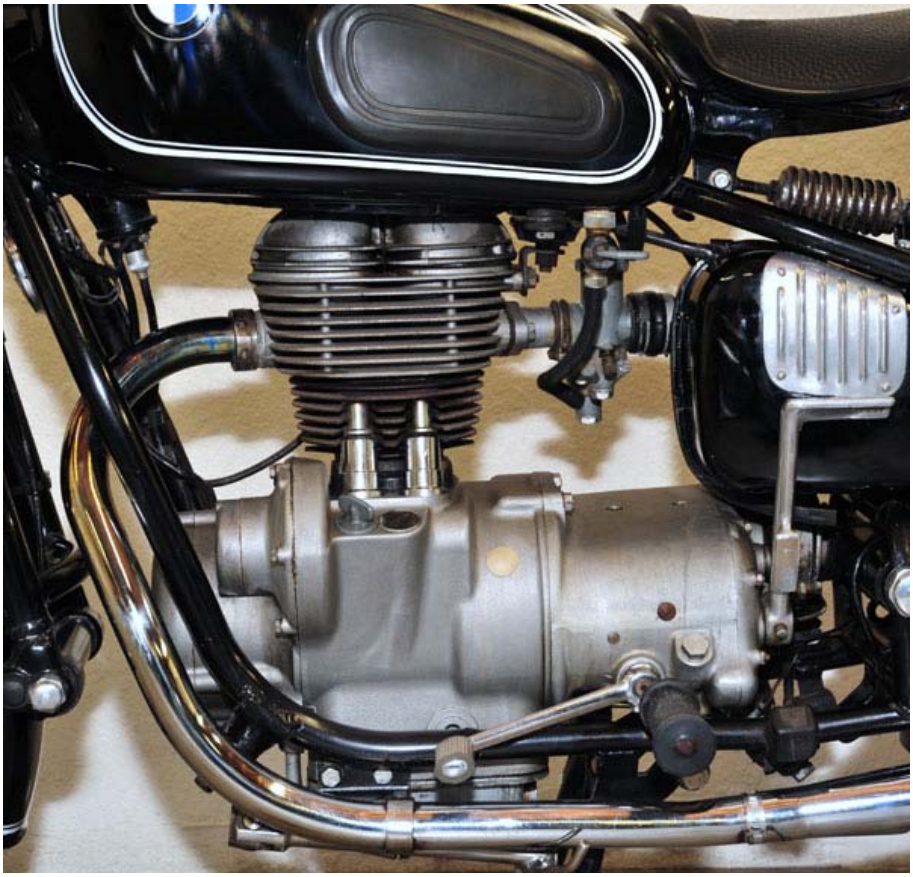
Chapter 3

Single Cylinder Engine and Straight-Three Engine

Single cylinder engine

A **single cylinder engine** is the most basic piston engine configuration of an internal combustion engine. It is often seen on motorcycles, Auto rickshaws, motor scooters, Mopeds, dirt bikes, go-karts, radio-controlled models and has many uses in portable tools and garden machinery. It has been used in cars and tractors.

Characteristics



BMW R27 single-cylinder motorcycle engine

Single cylinder engines are simple and compact, and will often deliver the maximum power possible within a given envelope. Cooling is simpler than with multiple cylinders, potentially saving further weight, especially if air-cooling can be used.

Single-cylinder engines require more flywheel effect than multi-cylinder engines and the rotating mass is relatively large, restricting acceleration and sharp changes of speed. In the basic arrangement they are prone to vibration - though in some cases it may be possible to control this with balance shafts.

Pros and Cons

Single cylinder engines are simple and economical in construction. The vibration they generate is acceptable in many applications while less acceptable in others. Counter-balance shafts and counterweights can be fitted but such complexities tend to counter the previously listed advantages.

Components such as the crankshaft of a single cylinder engine have to be nearly as strong as that in a multi-cylinder engine of the same capacity per cylinder, meaning that some parts are effectively four times heavier than they need to be for the total displacement of the engine. The single cylinder engine will almost inevitably develop a lower power to weight ratio than a multi-cylinder engine of similar technology. This can be a disadvantage in mobile operations, although it is of little significance in others and in most stationary applications.

Uses

Motorbike Horex "Regina" with one-cylinder-four-stroke-engine

Early motorcycles, automobiles and other applications such as marine engines all tended to be single cylinder. The configuration remains in widespread use in Auto rickshaws, motor scooters, Mopeds, dirt bikes, go-karts, radio-controlled models and is almost exclusively used in portable tools, along with garden machinery such as lawn mowers.

The bestselling motor-vehicle of the world, the Honda Super Cub, has a very fuel-efficient 49cc single cylinder engine and big-diameter 17inch-wheels (rolls smoother over obstacles).

Even big motorcycles with strong single-cylinder-engines are available today. There are Sport Bikes Like the KTM 690 Duke R which has 70hp-690cc-single-cylinder-engine and reaches 125mph (200km/h) with a curb weight of only 150kg. Or Dual-Sport Motorcycles like the BMW G650GS. And there are Classic motorcycles like the Royal-Enfield 500 Bullet with a classic long-stroke single-cylinder-engine.

Nearly all Auto rickshaws have very fuel-efficient single-cylinder-engines. Typical mileage for an Indian-made auto rickshaw is around 35 kilometers per liter of petrol (about 2.9 L per 100 km, or 82 miles per gallon [United States (wet measure), 100 miles per gallon Imperial (United Kingdom, Canada)].

Straight-three engine

Cylinder block of an inline three cylinder engine

A **straight-three engine**, also known as **inline-three engine**, or a **triple**, (abbreviated **I3** or **R3**) is a reciprocating piston internal combustion engine with three cylinders arranged in a straight line or plane, side by side.

Most inline-three engines employ a crank angle of 120°, and are thus rotationally balanced; however, since the three cylinders are offset from each other, the firing of the end cylinders induces a rocking motion from end to end, since there is no opposing cylinder moving in the opposite direction as in a rotationally balanced straight-six engine. The use of a balance shaft in an antiphase to that vibration produces a smoothly running engine.

An exception to the 120° crankshaft can be found in some of the inline-three engines made by motorcycle manufacturer Laverda. In these engines (sometimes referred to as 180° triples), the outer pistons rise and fall together like a 360° straight-two engine. The inner cylinder is offset 180° from the outer cylinders. In these engines, cylinder #1 fires 180°. Later, cylinder #2 fires, and then 180° later cylinder #3 fires. There is no power stroke on the final 180° of rotation.

Automobile use

A tuned version of a Saab inline-three cylinder two-stroke engine

Suzuki K10B

The smallest inline-three, four-stroke automobile engine was the 543 cubic centimetres (33.1 cu in) Suzuki *F5A*, which was first used in the 1979 Suzuki Alto/Fronte. Smart currently produces a diminutive 799 cubic centimetres (48.8 cu in) inline-three diesel engine, the smallest automotive diesel engine yet. Most inline-three engines fall below 1.2 litres, with a 1,198 cubic centimetres (73.1 cu in) Volkswagen Group unit seen as the largest petrol engine. A 1,779 cubic centimetres (108.6 cu in) diesel engine was produced by VM Motori to the 1984 Alfa Romeo 33 *1.8 TD*, the largest inline-three produced for automotive use.

Basic versions of the Suzuki Swift/Forsa and related Geo/Chevy Metro used an inline-three.

Some Daihatsu cars use inline-three engines. The Charade and the Mira/Cuore used (or are still fitted with) this engine type. Three-cylinder 1.0 litre diesel and turbo diesel engines were also offered in Daihatsu Charades. Korean cars Daewoo Tico, based on the 1988 Suzuki Alto, and later base versions of Daewoo Matiz also used inline-three 796 cubic centimetres (48.6 cu in) 41 horsepower (31 kW; 42 PS) S-TEC petrol engine.

The Volkswagen Group is known for using three cylinder petrol- and diesel engines; in the Audi A2, Volkswagen Polo, Volkswagen Fox, SEAT Ibiza and Škoda Fabia. The

engines in these cars ranges from 1.2 litre petrol with four valves per cylinder that deliver 47 to 65 kilowatts (64 to 88 PS; 63 to 87 bhp), to 1.4 TDI diesels= that deliver 51 to 66 kilowatts (69 to 90 PS; 68 to 89 bhp) and have turbos with variable vane geometry and deliver outstanding economy, this particular engine is used in small cars of all marques of the Volkswagen Group. The most innovative three cylinder engine the Volkswagen Group released was the 1.2 TDI diesel, it was one of the first all-aluminium diesel engines, and at the time of release it was the lightest and most economic engine in production. It won many awards and was used in the "3L" versions (from its diminutive fuel consumption of only 3 litres per 100 kilometres (94.2 mpg_{-imp}; 78.4 mpg_{-US})) of the Audi A2 and the Volkswagen Lupo.

Subaru also used an inline-three in the Subaru Justy and the export version of the Subaru Sambar, called the Subaru Sumo, using their Subaru EF engine.

Mitsubishi has also made extensive use of three cylinder engines.

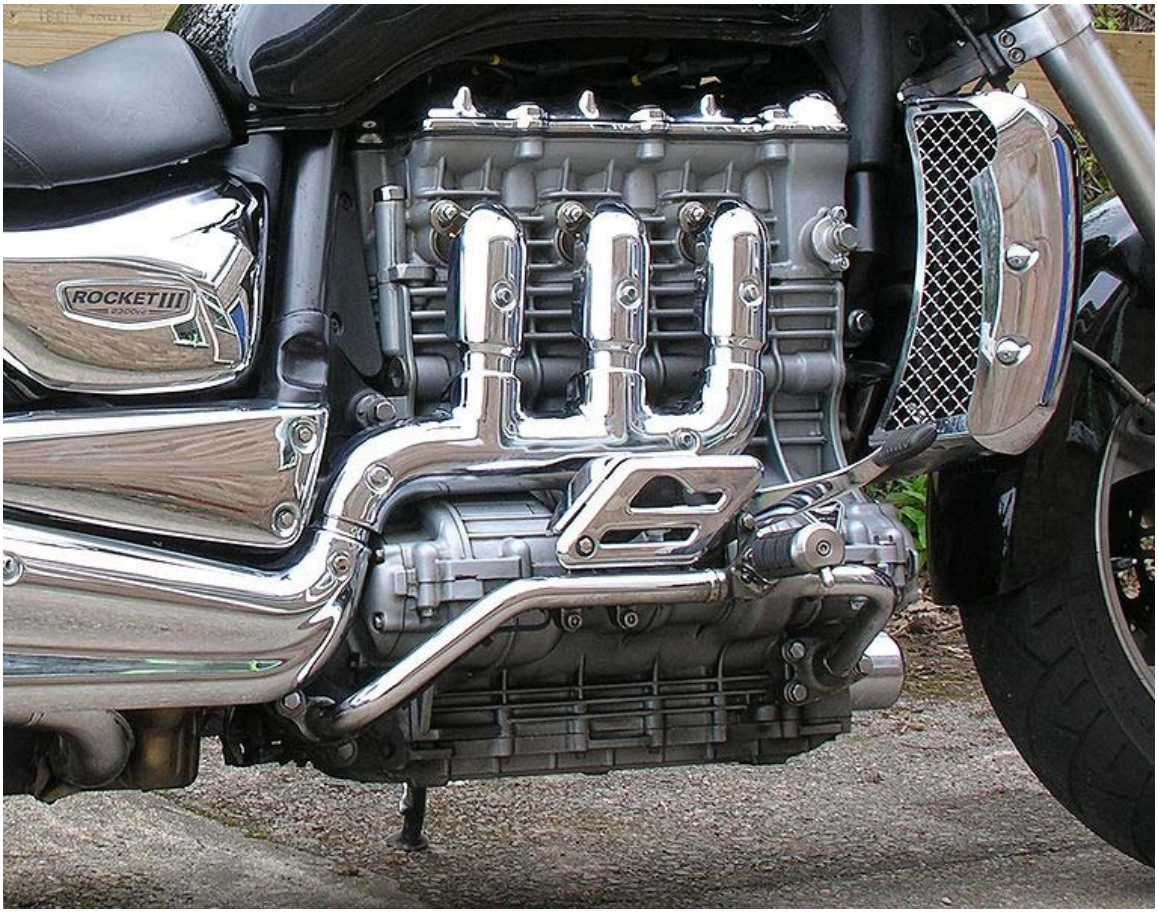
In the 1950s and 1960s, the Saab 93, Saab 95, Saab 96, and certain Dampf-Kraft-Wagen (DKW) automobiles were powered by inline-three-cylinder, two-stroke engines. Also, the Wartburg automobiles manufactured in Eastern Germany used this kind of engine.

The first-generation Honda Insight (2000–2006) used a 1.0 litre inline-three engine in conjunction with an electric motor in its hybrid system.

Toyota, Peugeot and Citroen are using a common inline-three-cylinder engine in models of Aygo, 107 and C1 respectively.

Currently, the only new three-cylinder car available in North America is the Smart fortwo.

Motorcycle use



Triumph Rocket III has a 2.3 L straight-three engine

Four-stroke

The four-stroke inline-three has been used by Aprilia, Laverda, Triumph, Yamaha, BMW, Benelli, Petronas, MV Agusta and BSA.

The Triumph Rocket III has a 2,294 cc (140.0 cu in) inline-three engine.

Two-stroke

Between 1972 and 1977, Suzuki made the inline-three water-cooled 750 cc GT750 and the air-cooled GT550 and GT380.

Between 1969 and 1978, Kawasaki triple motorcycles had inline-three air-cooled engines with capacities of 250 cc, 350 cc, 400 cc, 500 cc, and 750 cc.

Chapter 4

Variable Valve Timing

In internal combustion engines, **variable valve timing**, often abbreviated to **VVT**, is a generic term for an automobile piston engine technology. VVT allows the *lift*, *duration* or *timing* (in various combinations) of the intake and/or exhaust valves to be changed while the engine is in operation. Two-stroke engines use a power valve system to get similar results to VVT.

Overview

Piston engines normally use poppet valves for intake and exhaust. These are driven (directly or indirectly) by cams on a camshaft. The cams open the valves (*lift*) for a certain amount of time (*duration*) during each intake and exhaust cycle. The *timing* of the valve opening and closing is also important. The camshaft is driven by the crankshaft through timing belts, gears or chains.

The profile, or position and shape of the cam lobes on the shaft, is optimized for a certain engine revolutions per minute (RPM), and this tradeoff normally limits low-end torque, or high-end power. VVT allows the cam timing to change, which results in greater efficiency and power, over a wider range of engine RPMs.

An engine requires large amounts of air when operating at high speeds. However, the intake valves may close before enough air has entered each combustion chamber, reducing performance. On the other hand, if the camshaft keeps the valves open for longer periods of time, as with a racing cam, problems start to occur at the lower engine speeds. This will cause unburnt fuel to exit the engine since the valves are still open. This leads to lower engine performance and increased emissions. For this reason, pure racing engines which are designed to idle at speeds close to 2,000 rpm, cannot idle well at the lower speeds (around 800 rpm) expected of a road car.

Pressure to meet environmental goals and fuel efficiency standards is forcing car manufacturers to use VVT as a solution. Most simple VVT systems advance or retard the timing of the intake or exhaust valves. Others (like Honda's VTEC) switch between two

sets of cam lobes at a certain engine RPM. Furthermore Honda's i-VTEC can alter intake valve timing continuously.

History

Steam engines

The first variable valve timing systems came into existence in the nineteenth century on steam engines. Stephenson valve gear, as used on early steam locomotives, supported variable cutoff, that is, changes to the time at which the admission of steam to the cylinders is cut off during the power stroke. Early approaches to variable cutoff coupled variations in admission cutoff with variations in exhaust cutoff. Admission and exhaust cutoff were decoupled with the development of the Corliss valve. These were widely used in constant speed variable load stationary engines, with admission cutoff, and therefore torque, mechanically controlled by a centrifugal governor and trip valves. As poppet valves came into use, simplified valve gear using a camshaft came into use. With such engines, variable cutoff could be achieved with variable profile cams that were shifted along the camshaft by the governor.this is now coming in system.

Aircraft

Some versions of the Bristol Jupiter radial engine of the early 1920s incorporated variable valve timing gear, mainly to vary the inlet valve timing in connection with higher compression ratios. The Lycoming R-7755 engine had a Variable Valve Timing system consisting of two cams that can be selected by the pilot. One for take off, pursuit and escape, the other for economical cruising.

Automotive use

In 1958 Porsche made application for a German Patent, also applied for and published as British Patent GB861369 in 1959. The Porsche patent used an oscillating cam driven via a push/pull rod from an eccentric shaft or swash plate. The cam was Desmodromic having opening and closing cam surfaces which operated the valve by a bifurcated rocker and ball joint. Being Desmodromic meant there was no valve spring. The cam pivot was adjustable for height, as the push/pull rod length was constant this rotated the cam so the lift and duration increased. A compensating link moved the rocker pivot to match the cam's position. The adjustment of the cam pivot could be by mechanical linkage to a screw thread, hydraulic from engine driven pump with spill valve or from a engine speed governor. At present it is unknown if any working prototype was ever made.

Fiat was the first auto manufacturer to patent a functional automotive variable valve timing system which included variable lift. Developed by Giovanni Torazza in the late 1960s, the system used hydraulic pressure to vary the fulcrum of the cam followers (US Patent 3,641,988). The hydraulic pressure changed according to engine speed and intake pressure. The typical opening variation was 37%.

In September 1975, General Motors (GM) patented a system intended to vary valve lift. GM was interested in throttling the intake valves in order to reduce emissions. This was done by minimizing the amount of lift at low load to keep the intake velocity higher, thereby atomizing the intake charge. GM encountered problems running at very low lift, and abandoned the project.

Alfa Romeo was the first manufacturer to use a variable valve timing system in production cars (US Patent 4,231,330). The 1980 Alfa Romeo Spider 2.0 L had a mechanical VVT system in SPICA fuel injected cars sold in the United States. Later this was also used in the 1983 Alfetta 2.0 Quadrifoglio Oro models as well as other cars. The system was engineered by Ing Giampaolo Garcea in the 1970s.

Honda's REV motorcycle engine employed on the Japanese market-only Honda CBR400F in 1983 provided a technology base for VTEC.

In 1986, Nissan developed their own form of VVT with the VG30DE(TT) engine for their MID4 Concept. Nissan chose to focus their NVCS (Nissan Valve-Timing Control System) mainly on torque production at low to medium engine speeds, because, the vast majority of the time, automobile engines will not be operated at extremely high speeds. The NVCS system can produce a smooth idle and high amounts of torque at low to medium engine speeds. The VG30DE engine was first used in the 300ZX (Z31) 300ZR model in 1987. It was the first production car to use electronically controlled VVT technology. In 1987 Nissan also sold the Gloria, Leopard, and Cedric, all of which could come powered by the VG20DET engine which also utilized Nissans NVCS valve timing system.

The next step was taken in 1989 by Honda with the VTEC system. Honda had started production of a system that gives an engine the ability to operate on two completely different cam profiles, eliminating a major compromise in engine design. One profile designed to operate the valves at low engine speeds provides good road manners, low fuel consumption and low emissions output. The second is a high lift, long duration profile and comes into operation at high engine speeds to provide an increase in power output. The VTEC system was also further developed to provide other functions in engines designed primarily for low fuel consumption. The first VTEC engine Honda produced was the B16A which was installed in the Integra, CRX, and Civic hatchback available in Japan and Europe. In 1991 the Acura NSX powered by the C30A became the first VTEC equipped vehicle available in the US. VTEC can be considered the first "cam switching" system and is also one of only a few currently in production.

In 1991, Clemson University researchers patented the Clemson Camshaft which was designed to provide continuously variable valve timing independently for both the intake and exhaust valves on a single camshaft assembly. This ability makes it suitable for both pushrod and overhead cam engine applications.

In 1992, Porsche introduced VarioCam its 968 model which provided continuously variable valve timing for the intake valves.

In 1992, BMW introduced the VANOS system. Like the Nissan NVCS system it could provide timing variation for the intake cam in steps (or phases), the VANOS system differed in that it could provide one additional step for a total of three. Then in 1996 the Double Vanos system was introduced which significantly enhances emission management, increases output and torque, and offers better idling quality and fuel economy. Double Vanos was the first system which could provide electronically controlled, continuous timing variation for both the intake and exhaust valves.

Ford began using Variable Cam Timing in 1998 for the Ford Sigma engine and the Ford Zetec engine. Ford became the first manufacturer to use variable valve timing in a pickup-truck, with the top-selling Ford F-series in the 2004 model year. The engine used was the 5.4 L 3-valve Triton.

In 1999, Porsche introduced VarioCam Plus on its 911 Turbo which combined continuous valve timing and two stage valve lift on the intake valves.

In 2001, BMW introduced the Valvetronic system. The Valvetronic system can continuously and precisely vary intake valve lift, and in addition, the independent Double VANOS system can concurrently vary the timing for both the intake and exhaust valves. The precise control the system has over the intake valves allows for the intake charge to be controlled entirely by the intake valves, eliminating the need for a throttle valve and greatly reducing pumping loss. The reduction of pumping loss accounts for more than a 10% increase in power output and fuel economy.

In 2005, General Motors offered the first Variable Valve timing system for pushrod V6 engines, *LZE* and *LZ4*.

In 2007, DaimlerChrysler became the first manufacturer to produce a cam-in-block engine with independent control of exhaust cam timing relative to the intake. The 2008 Dodge Viper uses Mechadyne's concentric camshaft assembly to help boost power output to 600 bhp (450 kW).

In 2009, Fiat Powertrain Technologies introduced the Multiair system in Geneva Motor Show. The Multiair is a hydraulically-actuated variable valve timing system, which gives full control over valve lift and timing. The new technology is available in Alfa Romeo MiTo starting from September 2009.

In 2009, Porsche introduced an enhanced version of VarioCam Plus on its 911 GT3 including the previous variable valve timing and two stage valve lift on the intake valves but with additional variable timing of the exhaust valves.

Diesel engines

In 2010, Mitsubishi developed and started mass production of its 4N13 1.8 L DOHC I4 world's first passenger car diesel engine that features a variable valve timing system.

VVT implementations

- Aftermarket modifications — Conventional hydraulic tappet can be engineered to rapidly bleed-down for variable reduction of valve opening and duration.
- Alfa Romeo
  - Twin Cam — some versions are equipped with Variable Valve Timing technology.
  - Twin Spark — is equipped with Variable Valve Timing technology.
  - JTS — is equipped with Variable Valve Timing technology, both intake and exhaust.
  - Multiair continuously varies the timing of the inlet valve by changing oil pressure.
- BMW
  - Valvetronic — Provides continuously variable lift for the intake valves; used in conjunction with Double VANOS.
  - VANOS — Varies intake timing by rotating the camshaft in relation to the gear.
  - Double VANOS — Continuously varies the timing of the intake and exhaust valves.
- Daihatsu
  - DVVT — Daihatsu Variable Valve Timing. Continuously varies the timing of the intake camshaft, or both the intake and exhaust camshafts (depending on application).
- Fiat
  - "Twin Cam - VIS" engine - is equipped with Variable Valve Timing technology.
  - "StarJet" FIRE-based engine.
- Ford
  - VCT Variable Cam Timing — Varies valve timing by rotating the camshaft.
  - Ti-VCT Twin Independent Variable Camshaft with two fully variable camshafts used in Ford Sigma engine and Ford Duratec engine.
- Chrysler — Varies valve timing through the use of concentric camshafts developed by Mechadyne enabling dual-independent inlet/exhaust valve adjustment on the 2008 Dodge Viper.
- General Motors Corporation (GM)
  - VVT — Varies valve timing continuously throughout the RPM range for both intake and exhaust for improved performance in both overhead valve and overhead cam engine applications.
  - DCVCP (Double Continuous Variable Cam Phasing) — Varies intake and exhaust camshaft timing continuously with hydraulic vane type phaser; available on Family 1, Family 0, and Family II engines.
  - Alloytec — Continuously variable camshaft phasing for inlet cams; continuously variable camshaft phasing for inlet cams and exhaust cams (High Output Alloytec).
- Honda

    - VTEC — Varies duration, timing and lift by switching between two different sets of cam lobes.
    - VTEC-E — This system is designed solely for the purpose of improving fuel economy. A variation of the VTEC mechanism is used to create an offset of lift between the two intake valves, one valve opening only slightly to prevent accumulation of fuel in the intake port. The asymmetrical opening of the intake valves creates a powerful swirl in the combustion chamber and allows for a very lean intake charge to be used under certain conditions. Under normal operation the two intake valve rocker arms are locked together and both valves follow the normal lift cam profile.
    - i-VTEC — In high-output DOHC 4 cylinder engines, the i-VTEC system adds continuous intake cam phasing (timing) to traditional VTEC. In economy-oriented SOHC and DOHC 4-cylinder engines the i-VTEC system increases engine efficiency by delaying the closure of the intake valves under certain conditions and by using an electronically controlled throttle valve to reduce pumping loss. In SOHC V6 engines the i-VTEC system is used to provide Variable Cylinder Management which deactivates one bank of three cylinders during low demand operation.
    - Advanced VTEC — This is the latest Honda VVT system and is the most unusual of all the VTEC systems. Rather than switching between cam lobes the Advanced VTEC system uses intermediate rocker arms with a variable fulcrum to continuously vary intake valve timing, duration and lift.
- Hyundai MPI CVVT — Varies power, torque, exhaust system, and engine response.
- Iran Khodro
    - CVVT-i - Continuous Variable Valve Timing Intelligence which is used for EF7 & EF4 engines of the IKCO EF engines family.
- Kawasaki — Varies position of cam by changing oil pressure thereby advancing and retarding the valve timing, 2008 Concours 14 (also known as the 1400GTR).
- Lexus VVT-iE — Continuously varies the intake camshaft timing using an electric actuator.
- Mazda S-VT — Continually varies intake timing and crank angle using an oil control valve actuated by the ECU to control oil pressure.
- Mitsubishi MIVEC — Varies valve timing, duration and lift by switching between two different sets of cam lobes.
    - The 4B1 engine series uses a different variant of MIVEC which varies timing (phase) of both intake and exhaust camshafts continuously.
    - The 4N1 engine family is the world's first to feature a variable valve timing system applied to passenger car diesel engines.
- Nissan
    - N-VCT — Varies the rotation of the cam(s) only, does not alter lift or duration of the valves.
    - VVL — Varies timing, duration, and lift of the intake and exhaust valves by using two different sets of cam lobes.

    - CVTCS - introduced with the HR15DE, HR16DE, MR18DE and MR20DE engines in September 2004 on the Nissan Tiida and North American version named Nissan Versa (in 2007); and finally the Nissan Sentra (in 2007). Also used on the new MR16DDT
    - VVEL - introduced with the VQ37VHR Nissan VQ engine engine in 2007 on the Infiniti G37.
- Porsche
    - VarioCam — Varies intake timing by adjusting tension of a cam chain.
    - VarioCam Plus — Varies intake valve timing by rotating the cam in relation to the cam sprocket as well as duration, timing and lift of the intake and exhaust valves by switching between two different sets of cam lobes.
- Proton
    - Campro CPS — Varies intake valve timing and lift by switching between two sets of cam lobes without using rocker arms as in most variable valve timing systems. Debuted in the 2008 Proton Gen-2 CPS and the 2008 Proton Waja CPS.
    - VVT introduced in the Waja 1.8's F4P renault engine (Toyota supplies the VVT to renault)
- PSA Peugeot Citroën CVVT — Continuous variable valve timing.
- Renault Clio Renault Sport 172, 172 Cup, 182, 182 Cup, Trophy, 197, 197 Cup, 200, and Clio V6 Mk2 VVT — Megane 1.6 vvt variable valve timing. Clio Mk4 Dynamique S 1.6 VVT. RS Twingo 133 1.6 VVT
- Rover VVC — Varies timing with an eccentric disc.
- Suzuki — VVT — Suzuki M engine
- Subaru
    - AVCS — Varies timing (phase) with hydraulic pressure, used on turbocharged and six-cylinder Subaru engines.
    - AVLS — Varies duration, timing and lift by switching between two different sets of cam lobes (similar to Honda VTEC). Used by non-turbocharged Subaru engines.
- Toyota
    - VVT — Toyota 4A-GE 20-Valve engine introduced VVT in the 1992 Corolla GT-versions.
    - VVT-i — Continuously varies the timing of the intake camshaft, or both the intake and exhaust camshafts (depending on application).
    - VVTL-i — Continuously varies the timing of the intake valves. Varies duration, timing and lift of the intake and exhaust valves by switching between two different sets of cam lobes.
    - Valvematic
- Vauxhall - VVT used in the facelift Vectra 1.8 engines, Astra's and Corsa's.
- Volkswagen Group — VVT introduced with later revisions of the 1.8t engine, and the 30-valve 2.8 L V6. Similar to VarioCam, the intake timing intentionally runs advanced and a retard point is calculated by the ECU. A hydraulic tensioner retards the intake timing. Most modern VW Group petrol engines now include

VVT on either the inlet cam, or both inlet and exhaust cams, as in their V6, V8 and V10 engines.

- Volvo
  - CVVT — Continuous variable valve timing on intake and/or exhaust camshafts (depending on application).
  - CPS — Changes valve timing, duration and lift of the intake valves by switching between two different sets of cam lobes. Same basic technology as Porsches VarioCam Plus with switching direct-acting tappets. To date this is only used on Volvos short inline-6 (SI6) naturally-aspirated 3.2 L engine.
- Yamaha — VCT (Variable Cam Timing) Varies position of cam thereby advancing and retarding the valve timing.

Chapter 5

Gasoline Direct Injection

In internal combustion engines, **gasoline direct injection** (GDI), also known as **petrol direct injection** or **direct petrol injection**, is a variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.

In some applications, gasoline direct injection enables a stratified fuel charge (ultra lean burn) combustion for improved fuel efficiency, and reduced emission levels at low load.

Theory of operation

The major advantages of a GDI engine are increased fuel efficiency and high power output. In addition, the cooling effect of the injected fuel and the more evenly dispersed mixtures allow for more aggressive ignition timing curves. Emissions levels can also be more accurately controlled with the GDI system. The cited gains are achieved by the precise control over the amount of fuel and injection timings that are varied according to the load conditions. In addition, there are no throttling losses in some GDI engines, when compared to a conventional fuel injected or carbureted engine, which greatly improves efficiency, and reduces 'pumping losses' in engines without a throttle plate. Engine speed is controlled by the engine control unit/engine management system (EMS), which regulates fuel injection function and ignition timing, instead of having a throttle plate that restricts the incoming air supply. Adding this function to the EMS requires considerable enhancement of its processing and memory, as direct injection plus the engine speed management must have very precise algorithms for good performance and drivability.

The engine management system continually chooses among three combustion modes: ultra lean burn, stoichiometric, and full power output. Each mode is characterized by the air-fuel ratio. The stoichiometric air-fuel ratio for gasoline is 14.7:1 by weight, but ultra lean mode can involve ratios as high as 65:1 (or even higher in some engines, for very limited periods). These mixtures are much leaner than in a conventional engine and reduce fuel consumption considerably.

- **Ultra lean burn** mode is used for light-load running conditions, at constant or reducing road speeds, where no acceleration is required. The fuel is not injected at the intake stroke but rather at the latter stages of the compression stroke, so that the small amount of air-fuel mixture is optimally placed near the spark plug. This stratified charge is surrounded mostly by air, which keeps the fuel and the flame away from the cylinder walls for lowest emissions and heat losses. The combustion takes place in a toroidal (donut-shaped) cavity on the piston's surface. The cavity is displaced to one side of the piston, the side that has the fuel injector. This technique enables the use of ultra-lean mixtures that would be impossible with carburetors or conventional fuel injection.
- **Stoichiometric** mode is used for moderate load conditions. Fuel is injected during the intake stroke, creating a homogenous fuel-air mixture in the cylinder. From the stoichiometric ratio, an optimum burn results in a clean exhaust emission, further cleaned by the catalytic converter.
- **Full power** mode is used for rapid acceleration and heavy loads (as when climbing a hill). The air-fuel mixture is homogenous and the ratio is slightly richer than stoichiometric, which helps prevent knock (pinging). The fuel is injected during the intake stroke.

Direct injection may also be accompanied by other engine technologies such as variable valve timing (VVT) and tuned/multi path or variable length intake manifolding (VLIM, or VIM). Water injection or (more commonly) exhaust gas recirculation (EGR) may help reduce the high nitrogen oxides (NOx) emissions that can result from burning ultra lean mixtures.

It is also possible to inject more than once during a single cycle. After the first fuel charge has been ignited, it is possible to add fuel as the piston descends. The benefits are more power and economy, but certain octane fuels have been seen to cause exhaust valve erosion. For this reason, most companies have ceased to use the Fuel Stratified Injection (FSI) operation during normal running.

Tuning up an early generation FSI power plant to generate higher power is difficult, since the only time it is possible to inject fuel is during the induction phase. Conventional injection engines can inject throughout the 4-stroke sequence, as the injector squirts onto the back of a closed valve. A direct injection engine, where the injector injects directly into the cylinder, is limited to the suction stroke of the piston. As the RPM increases, the time available to inject fuel decreases. Newer FSI systems that have sufficient fuel pressure to inject even late in compression phase do not suffer to the same extent; however, they still do not inject during the exhaust cycle (they could but it would just waste fuel). Hence, all other factors being equal, an FSI engine needs higher-capacity injectors to achieve the same power as a conventional engine.

History

Early systems

The first use of direct gasoline injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925. Hesselman engines used the ultra lean burn principle and injected the fuel in the end of the compression stroke and then ignited it with a spark plug, it was often started on gasoline and then switched over to run on diesel or kerosene. The Hesselman engine was a low compression design constructed to run on heavy fuel oils. Direct gasoline injection was used on production aircraft during WWII, with German (Junkers Jumo 210, Daimler-Benz DB 601, both 1937), Soviet (Shvetsov ASh-82, 1943, Chemical Automatics Design Bureau - KB Khimavtomatika) and US (Wright R-3350, 1944) designs. The first automotive direct injection system used to run on gasoline was developed by Bosch, and was introduced by Goliath and Gutbrod in 1952. The 1955 Mercedes-Benz 300SL, the first sports car to use fuel injection, used direct injection. The Bosch fuel injectors were placed into the bores on the cylinder wall used by the spark plugs in other Mercedes-Benz six-cylinder engines (the spark plugs were relocated to the cylinder head). Later, more mainstream applications of fuel injection favored the less-expensive indirect injection methods.

In the early 1970s, research was conducted with the backing of American Motors Corporation (AMC) to develop a Straticharge Continuous Fuel-Injection (SCFI) system. The conventional spark ignited internal combustion I6 engine was a modified with a redesigned cylinder head. The system incorporated a mechanical device that automatically responded to the engine’s airflow and loading conditions with two separate fuel-control pressures supplied to two sets of continuous-flow injectors. Flexibility was designed into the SCFI system for trimming it to a particular engine. Prototype "straticharge" engine road testing was performed using a 1973 AMC Hornet, but the mechanical fuel controls had teething problems.

During the late 1970s, the Ford Motor Company developed a stratified-charge engine they called "ProCo" (programmed combustion), utilizing a unique high-pressure pump and direct injectors. One hundred Crown Victoria cars were built at Ford's Atlanta Assembly in Hapeville, Georgia using a ProCo V8 engine. The project was canceled for several reasons: electronic controls, a key element, were in their infancy; pump and injector costs were extremely high; and lean combustion produced nitrogen oxides in excess of near future United States Environmental Protection Agency (EPA) limits. The three-way catalytic converter proved to be a less expensive solution.

Later systems

In **1996** gasoline direct injection reappeared in the automotive market. Mitsubishi was the first with a **GDI** engine in the Japanese market with its Galant/Legnum's *4G93* 1.8 L inline-four. It was subsequently brought to Europe in 1997 in the Carisma, although Europe's then high-sulfur unleaded fuel led to emissions problems, and fuel efficiency was less than expected. It also developed the first six-cylinder GDI powerplant, the *6G74*

3.5 L V6, in 1997. Mitsubishi applied this technology widely, producing over one million GDI engines in four families by 2001.

In **1997** Nissan released the Leopard featuring the VQ30DD equipped with direct injection.

In **1998**, Toyota's D4 direct injection system first appeared on various Japanese market vehicles equipped with the *SZ* and *NZ* engines. Toyota later introduced its D4 system to European markets with the *1AZ-FSE* engine found in the 2001 Avensis. and US markets in 2005 with the *3GR-FSE* engine found in the Lexus GS 300. Toyota's *2GR-FSE* V6 uses a more advanced direct injection system, which combines both direct and indirect injection using two fuel injectors per cylinder, a traditional port fuel injector (low pressure) and a direct fuel injector (high-pressure) in a system known as D4-S.

In **1999**, Renault introduced the 2.0 IDE (Injection Direct Essence), first on the Megane. Rather than following the lean burn approach, Renault's design uses high ratios of exhaust gas recirculation to improve economy at low engine loads, with direct injection allowing the fuel to be concentrated around the spark. Later gasoline direct injection engines have been tuned and marketed for their high performance as well as increased fuel efficiency. PSA Peugeot Citroën, Hyundai and Volvo licensed Mitsubishi's GDI technology in 1999. Although other companies have since developed gasoline direct injection engines, the acronym 'GDI' (with an uppercase final "I") remains a registered trademark of Mitsubishi Motors.

In **2000**, the Volkswagen Group introduced its gasoline direct injection engine in the Volkswagen Lupo, a 1.4 L inline-four unit, under the product name "Fuel Stratified Injection" (FSI). The technology was adapted from Audi's Le Mans prototype race car R8. Volkswagen Group marques use direct injection in its 2.0 L FSI turbocharged and naturally-aspirated four-cylinder engines. Later, a 2.0 L inline-four unit was introduced in the model year 2003 Audi A4. PSA Peugeot Citroën introduced its first GDi (HPi) engine in 2000 in the Citroën C5 and Peugeot 406. It was a 2.0-liter 16-valve EW10 D unit with 140 hp (104 kW), the system was licensed from Mitsubishi.

In **2001**, Ford introduced its first European Ford engine to use direct injection technology, badged SCi (Smart Charge injection) for Direct-Injection-Spark-Ignition (DISI). The range will include some turbocharged derivatives, including the 1.1 L, three-cylinder turbocharged unit showcased at the 2002 Geneva Show. This new 1.8 L Duratec SCi naturally aspirated engine made its production debut in the Ford Mondeo in 2003.

In **2002**, the Alfa Romeo 156 with a direct-injection engine, the JTS (Jet Thrust Stoichiometric) went on sale and today the technology is used on almost every Alfa Romeo engine.

In **2003**, BMW introduced a low-pressure gasoline direct injection N73 V12. This initial BMW setup could not enter lean-burn mode, but the company introduced its second-generation High Precision Injection (HPI) system on the updated N52 straight-6 in 2006,

which used high-pressure injectors. This system surpasses many others with a wider envelope of lean-burn time, increasing overall efficiency. PSA is cooperating with BMW on a new line of engines that made its first appearance in the 2007 MINI Cooper S. Honda released their own direct injection system on the Stream sold in Japan. Honda's fuel injector is placed directly atop the cylinder at a 90-degree angle rather than a slanted angle.

Since **2004**, General Motors has released three such direct injected engines: in 2004, a 155 hp (116 kW) version of the 2.2 L Ecotec used in the Opel/Vauxhall Vectra and Signum in 2005, a 2.0 L turbocharged Ecotec for the new Opel GT, Pontiac Solstice GXP, and the Saturn Sky Red Line, in 2007 the same engine was used in the Super Sport versions of the Chevrolet Cobalt and the HHR. Also in 2007, the 3.6 L LLT became available in the redesigned Cadillac CTS and STS. The 3.6 L was added to the 2009 model GMC Acadia, Chevrolet Traverse, Saturn Outlook, Buick Enclave, and the 2010 Chevy Camaro. In 2004 Isuzu produced the first GDi engine sold in a mainstream American vehicle, standard on the 2004 Axiom and optional on the 2004 Rodeo. Isuzu claimed the benefit of GDi is that the vaporizing fuel has a cooling effect, allowing a higher compression ratio (10.3:1 versus 9.1:1) that boosts output by 20 hp (15 kW), and that 0-to-60 mph times drop from 8.9 to just 7.5 seconds, with the quarter-mile being cut from 16.5 to 15.8 seconds.

In **2005**, Mazda began to use their own version of direct-injection in the Mazdaspeed6 and later on the CX-7 sport-utility, and the new Mazdaspeed3 in the US and European market. It is referred to as Direct Injection Spark Ignition (DISI).

In **2006**, BMW released the new N54 twin-turbo-charged direct injection inline-six engine for its 335i Coupe and later for the 335i Sedan, 535i series and the 135i models. Mercedes-Benz released its direct injection system (Charged Gasoline Injection, or "CGI") on the CLS 350 CGI featuring common rail, piezo-electric direct fuel injectors. The CLS 350 CGI offers 292 BHP versus 272 BHP for the CLS 350, with reduced carbon dioxide emissions and improved fuel economy.

In **2007**, Ford introduced its new Ford EcoBoost engine technology designed for a range of global vehicles (from small cars to large trucks). The engine first appeared in the 2007 Lincoln MKR Concept under the name *TwinForce*. The new global EcoBoost family of 4-cylinder and 6-cylinder engines features turbocharging and direct injection technology (GTDI - Gasoline Turbocharged Direct Injection). A 2.0 L version was unveiled in the 2008 Ford Explorer America Concept.

In **2008**, BMW released the X6 xDrive50i equipped with a direct injected twin turbo N63 V8 engine.

In **2009**, Ferrari began selling the front-engine California with a direct injection system, and announced that its new 458 Italia car will also feature a direct injection system, a first for Ferrari mid-rear engine setups. Porsche also began selling the 997 and Cayman equipped with direct injection. Ford produced the new generation Taurus SHO and Flex

with a 3.5 L twin-turbo EcoBoost V-6 with direct injection. Holden has also added two direct injection engines as standard on the V6 variant Commodores under the name of SIDI or Spark Ignition Direct Injection. The Infiniti Essence concept car is powered by a direct injected twin turbo V6. The Jaguar Land Rover AJ-V8 Gen III 5.0 L engine (introduced in August 2009 for the 2010 model year) features spray-guided direct injection.

In **2010** Infiniti will produce the M56 which includes DI. Motus Motorcycles is developing, with Katech Engines, a direct-injected V4 engine named the KMV4 as the powertrain for their MST motorcycles. The Hyundai Sonata 2011 model will come with GDI engines. Hyundai's Theta I-4 engine family is a proprietary design, engineered in Namyang, Korea and currently in production for applications all over the world at volumes exceeding 2 million annually. The new Theta II 2.4L GDI engine is a derivative of the Theta with major upgrades in technology and architecture. It features a unique block, valvetrain, front-end accessory drive (FEAD), intake manifold, pistons, rods, crankshaft, variable induction system, and catalyst.

In two-stroke engines

The benefits of direct injection are even more pronounced in two-stroke engines, because it eliminates much of the pollution they cause. In conventional two-strokes, the exhaust and intake ports are both open at the same time, at the bottom of the piston stroke. A large portion of the fuel/air mixture entering the cylinder from the crankcase through the intake ports goes directly out, unburned, through the exhaust port. With direct injection, only air comes from the crankcase, and fuel is not injected until the piston rises and all ports are closed.

Some Goliath two stroke cars built in the early 1950s had direct injection, but their engines were soon superseded by four strokes.

Two types of GDi are used in two-strokes: low-pressure air-assisted, and high-pressure. The former, developed by Orbital Engine Corporation of Australia (now Orbital Corporation) injects a mixture of fuel and compressed air into the combustion chamber. When the air expands it atomizes the fuel. The Orbital system is used in motor scooters manufactured by Aprilia, Piaggio, Peugeot and Kymco, in outboard motors manufactured by Mercury and Tohatsu, and in personal watercraft manufactured by Bombardier Recreational Products (BRP).

In the early 1990s, Ficht GmbH of Kirchseeon, Germany developed a high-pressure direct injector for use with two stroke engines. Outboard Marine Corporation (OMC) licensed the technology in 1995 and introduced it on a production outboard engine in 1996. OMC purchased a controlling interest in Ficht in 1998. Beset by extensive warranty claims for its Ficht outboards and prior and concurrent management-financial problems, OMC declared bankruptcy in December 2000 and the engine manufacturing portion and brands (Evinrude Outboard Motors and Johnson Outboards), including the Ficht technology, were purchased by BRP in 2001.

Evinrude introduced the E-Tec system, an improvement to the Ficht fuel injection, in 2003, based on U.S. patent 6,398,511. In 2004, Evinrude received the EPA Clean Air Excellence Award for their outboards utilizing the E-Tec system. The E-Tec system has recently also been adapted for use in performance two-stroke snowmobiles.

Yamaha also has a high-pressure direct injection (HPDI) system for two-stroke outboards. It differs from the Ficht/E-Tec and Orbital direct injection systems because it uses a separate, belt driven, high-pressure, mechanical fuel pump to generate the pressure necessary for injection in a closed chamber. This is similar to most current 4-stroke automotive designs.

EnviroFit, a non-profit corporation sponsored by Colorado State University, has developed direct injection retrofit kits for two-stroke motorcycles in a project to reduce air pollution in Southeast Asia, using technology developed by Orbital Corporation of Australia. The World Health Organization says air pollution in Southeast Asia and the Pacific causes 537,000 premature deaths each year. The 100-million two-stroke taxis and motorcycles in that part of the world are a major cause.

Future

Twin-fuel engines

Code named Bobcat, the new twin-fuel engine from Ford is based on a 5.0L V8 engine block but uses E85 cylinder injection and gasoline port injection. The engine was co-developed with Ethanol Boosting Systems, LLC of Cambridge, Massachusetts, which calls its trademarked process DI Octane Boost. The direct injection of ethanol increases the octane of regular gasoline from 88-91 octane to more than 150 octane. The Bobcat project was unveiled to the United States Department of Energy and the SAE International in April 2009.

Formula One

As part of the rule changes under discussion for the 2013 season, GDI has been mentioned as a potential technology of interest by Ferrari.

Chapter 6

VTEC

VTEC (**Variable Valve Timing and Lift Electronic Control**) is a valvetrain system developed by Honda to improve the volumetric efficiency of a four-stroke internal combustion engine. This system uses two camshaft profiles and electronically selects between the profiles. This was the first system of its kind. Different types of variable valve timing and lift control systems have also been produced by other manufacturers (MIVEC from Mitsubishi, AVCS from Subaru, VVTL-i from Toyota, VarioCam Plus from Porsche, VVC from Rover Group, VVL from Nissan, etc.). It was invented by Honda R&D engineer Ikuo Kajitani.

History

VTEC, the original Honda variable valve control system, originated from REV (Revolution-modulated valve control) introduced on the CBR400 in 1983 known as HYPER VTEC. In the regular four-stroke automobile engine, the intake and exhaust valves are actuated by lobes on a camshaft. The shape of the lobes determines the timing, lift and duration of each valve. Timing refers to an angle measurement of when a valve is opened or closed with respect to the piston position (BTDC or ATDC). Lift refers to how much the valve is opened. Duration refers to how long the valve is kept open. Due to the behavior of the working fluid (air and fuel mixture) before and after combustion, which have physical limitations on their flow, as well as their interaction with the ignition spark, the optimal valve timing, lift and duration settings under low RPM engine operations are very different from those under high RPM. Optimal low RPM valve timing, lift and duration settings would result in insufficient filling of the cylinder with fuel and air at high RPM, thus greatly limiting engine power output. Conversely, optimal high RPM valve timing, lift and duration settings would result in very rough low RPM operation and difficult idling. The ideal engine would have fully variable valve timing, lift and duration, in which the valves would always open at exactly the right point, lift high enough and stay open just the right amount of time for the engine speed in use.

VTEC was initially designed to increase the power output of an engine to 100 PS/liter or more while maintaining practicality for use in mass production vehicles. Some later variations of the system were designed solely to provide improvements in fuel efficiency,

or increased power output. In practice, a fully variable valve timing engine is difficult to design and implement.

The opposite approach to variable timing is to produce a camshaft which is better suited to high RPM operation. This approach means that the vehicle will run very poorly at low RPM (where most automobiles spend much of their time) and much better at high RPM. VTEC is the result of an effort to marry high RPM performance with low RPM stability.

Additionally, Japan has a tax on engine displacement, requiring Japanese auto manufacturers to make higher-performing engines with lower displacement. In cars such as the Toyota Supra and Nissan 300ZX, this was accomplished with a turbocharger. In the case of the Mazda RX-7 and RX-8, a rotary engine was used. VTEC serves as yet another method to derive very high specific output (power/unit displacement) from smaller-displacement engines.

DOHC VTEC

The VTEC system is a simple method of endowing the engine with multiple camshaft profiles optimized for low and high RPM operations. Instead of one cam lobe actuating each valve, there are two: one optimized for low-RPM stability & fuel efficiency; the other designed to maximize high-RPM power output. Switching between the two cam lobes is controlled by the ECU which takes account of engine oil pressure, engine temperature, vehicle speed, engine speed and throttle position. Using these inputs, the ECU is programmed to switch from the low lift to the high lift cam lobes when the conditions mean that engine output will be improved. At the switch point a solenoid is actuated which allows oil pressure from a spool valve to operate a locking pin which binds the high RPM cam follower to the low RPM ones. From this point on, the poppet valve opens and closes according to the high-lift profile, which opens the valve further and for a longer time. The switch-over point is variable, between a minimum and maximum point, and is determined by engine load. The switch back from high to low RPM cams is set to occur at a lower engine speed than the up-switch (hysteresis) to avoid a situation in which the engine is asked to operate continuously at or around the switch-over point.

Introduced as a DOHC system in the 1989 Honda Integra and Civic CRX SiR (Japan) and 1.6i-VT (Europe) models, which used a 150 bhp (110 kW) variant of the B16A engine (B16A1). The US market saw the first VTEC system with the introduction of the 1991 Acura NSX, which used a 3 liter DOHC VTEC V6 with 280 bhp (210 kW). DOHC VTEC engines soon appeared in other vehicles, such as the 1992 Acura Integra GS-R (B17A1 1.7 liter engine), and later in the 1992 Honda Prelude VTEC (H22A 2.2 liter engine with 195 hp) and Honda Del Sol VTEC (B16A2 1.6 liter engine). The Integra Type R (1997–2001) available in the Japanese market produces 200 bhp (149 kW; 203 PS) using a B18C5 1.8 liter engine. Honda has also continued to develop other varieties and today offers several varieties of VTEC, such as i-VTEC and i-VTEC Hybrid.

SOHC VTEC

As popularity and marketing value of the VTEC system grew, Honda applied the system to SOHC (Single Over Head Cam) engines, which share a common camshaft for both intake and exhaust valves. The trade-off was that Honda's SOHC engines only benefitted from the VTEC mechanism on the intake valves. This is because VTEC requires a third center rocker arm and cam lobe (for each intake and exhaust side), and in the SOHC engine, the spark plugs are situated between the two exhaust rocker arms, leaving no room for the VTEC rocker arm. Additionally, the center lobe on the camshaft can only be utilized by either the intake or the exhaust, limiting the VTEC feature to one side.

However, beginning with the J37A4 3.7L SOHC V6 engine introduced on all 2009 Acura TL SH-AWD models, SOHC VTEC was incorporated for use with intake and exhaust valves. The intake and exhaust rocker shafts contain primary and secondary intake and exhaust rocker arms, respectively. The primary rocker arm contains the VTEC switching piston, while the secondary rocker arm contains the return spring. The term "primary" does not refer to which rocker arm forces the valve down during low-RPM engine operation. Rather, it refers to the rocker arm which contains the VTEC switching piston and receives oil from the rocker shaft.

The primary exhaust rocker arm contacts a low-profile camshaft lobe during low-RPM engine operation. Once VTEC engagement occurs, the oil pressure flowing from the exhaust rocker shaft into the primary exhaust rocker arm forces the VTEC switching piston into the secondary exhaust rocker arm, thus locking both exhaust rocker arms together. The high-profile camshaft lobe which normally contacts the secondary exhaust rocker arm alone during low-RPM engine operation is able to move both exhaust rocker arms together which are locked as a unit.

The secondary intake rocker arm contacts a low-profile camshaft lobe during low-RPM engine operation. Once VTEC engagement occurs, the oil pressure flowing from the intake rocker shaft into the primary intake rocker arm forces the VTEC switching piston into the secondary intake rocker arm, thus locking both intake rocker arms together. The high-profile camshaft lobe which normally contacts the primary intake rocker alone during low-RPM engine operation is able to move both intake rocker arms together which are locked as a unit.

The difficulty of incorporating VTEC for both the intake and exhaust valves in a SOHC engine has been removed on the J37A4 by a novel design of the intake rocker arm. Each exhaust valve on the J37A4 corresponds to one primary and one secondary exhaust rocker arm. Therefore, there are a total of twelve primary exhaust rocker arms and twelve secondary exhaust rocker arms.

However, each secondary intake rocker arm is shaped similar to a "Y" which allows it to contact two intake valves at once. One primary intake rocker arm corresponds to each secondary intake rocker arm. As a result of this design, there are only six primary intake rocker arms and six secondary intake rocker arms.

VTEC-E

It is a version of SOHC VTEC, which was used to increase efficiency at low RPM. At low RPM, one of the two intake valves is only allowed to open a very small amount, increasing the fuel/air atomization in the cylinder and thus allowing a leaner mixture to be used. As the engine's speed increases, both valves are needed to supply sufficient mixture. A sliding pin, which is pressured by oil, as in the regular VTEC, is used to connect both valves together and allows the full opening of the second valve.

3-Stage VTEC

It is a version of VTEC using 3 different cam profiles to control intake valve timing and lift. Due to this version of VTEC being on a SOHC valve head, space was limited and so VTEC can only modify the opening and closing of the intake valves. This version of VTEC combines the fuel economy benefits of VTEC-E and the performance of VTEC. From idle to 2500-3000RPM, depending on load conditions, one intake valve fully opens while the other just slightly, enough to prevent pooling of fuel behind the valve, also called 12 valve mode. This 12 Valve mode results in swirl of the intake charge which increases combustion efficiency resulting in improved low end torque and better fuel economy. At 3000-5400 RPM, depending on load, one of the VTEC solenoids engages which causes the 2nd valve (the one that barely opened before) to lock onto the first valve's camshaft lobe so now both valves share the same camshaft profile, with this mode also being called 4 valve mode, lending itself to improved mid-range power. At 5500-7000 RPM, the second VTEC solenoid engages (both solenoids now engaged) so that both intake valves are using a middle, third camshaft lobe. This camshaft lobe is a high performance lobe which is used to provide peak power at the top end of the RPM range.

i-VTEC

(intelligent-VTEC) introduced continuously variable camshaft phasing on the intake cam of DOHC VTEC engines. The technology first appeared on Honda's K-series four cylinder engine family in 2001 (2002 in the U.S.). In the United States, Honda first debuted the technology on the 2003 Honda Civic Si EP3 with the economy version.

Valve lift and duration are still limited to distinct low- and high-RPM profiles, but the intake camshaft is now capable of advancing between 25 and 50 degrees (depending upon engine configuration) during operation. Phase changes are implemented by a computer controlled, oil driven adjustable cam gear. Phasing is determined by a combination of engine load and rpm, ranging from fully retarded at idle to somewhat advanced at full throttle and low RPM. The effect is further optimization of torque output, especially at low and midrange RPM.

K-series

The K-Series motors have two different types of i-VTEC systems implemented. The first is for the performance motors like in the RSX Type S or the Civic Si and the other is for

economy motors found in the CR-V or Accord. The performance i-VTEC system is basically the same as the DOHC VTEC system of the B16A's; both intake and exhaust have 3 cam lobes per cylinder. However the valvetrain has the added benefit of roller rockers and continuously variable intake cam timing. Performance i-VTEC is a combination of conventional DOHC VTEC with VTC.

The economy i-VTEC is more like the SOHC VTEC-E in that the intake cam has only two lobes, one very small and one larger, as well as no VTEC on the exhaust cam. The two types of motor are easily distinguishable by the factory rated power output: the performance motors make around 200 hp (150 kW) or more in stock form and the economy motors do not make much more than 160 hp (120 kW) from the factory.

R-series

The new SOHC i-VTEC implementation is an entirely new implementation that was first introduced on the 2006 Honda Civic's R-series four cylinder SOHC engines. This implementation uses the so-called "fuel economy cam" and "high output cam" on one of the two intake valves of each cylinder (another intake valve is fixed). The "fuel economy cams" are designed to retard the closure of one intake valve and are activated between 1000-3500 RPM and under low load conditions. When "fuel economy cams" are activated, the intake valve closes well after the piston has started moving upwards in the compression stroke. During this time, the drive-by-wire throttle valve is open wider than normal. Due to the delayed closing of intake valve, a part of the intake mixture that has entered the combustion chamber is forced out again into the intake manifold. That way, the engine "emulates" a lower displacement than its actual one (its operation is also similar to an Atkinson cycle engine, with uneven compression and combustion strokes), which reduces pumping losses thus reducing fuel consumption and increases its efficiency. VTEC-off on the R18A means it can be considered to be running "high output cams". When the right conditions are achieved for fuel economy, VTEC engages the 2nd set, the 'low' or 'economy' cams. Thus VTEC-on on the R18A means it is running low cams.

According to Honda, this measure alone can reduce pumping losses by 16%. Under heavier loads, the engine switches back into its "high output cams", and it operates like a regular 4 stroke Otto cycle engine. This implementation of i-VTEC was initially introduced in the R18A1 engine found under the hood of the 8th generation Civic, with a displacement of 1.8 L and an output of 140 PS (100 kW; 140 hp). Recently, another variant was released, the 2.0 L R20A2 with an output of 150 PS (110 kW; 150 hp), which powers the EUDM version of the all-new CRV. SOHC i-VTEC

With the continued introduction of vastly different i-VTEC systems, one may assume that the term is now a catch-all for creative valve control technologies from Honda.

i-VTEC with Variable Cylinder Management (VCM)

In 2003, Honda introduced an i-VTEC V6 (an update of the J-series) that includes Honda's cylinder deactivation technology which closes the valves on one bank of (3) cylinders during light load and low speed (below 80 km/h (50 mph)) operation. According to Honda "VCM technology works on the principle that a vehicle only requires a fraction of its power output at cruising speeds. The system electronically deactivates cylinders to reduce fuel consumption. The engine is able to run on 3,4, or all 6 cylinders based on the power requirement. Essentially getting the best of both worlds. V6 power when accelerating or climbing, as well as the efficiency of a smaller engine when cruising." The technology was originally introduced to the US on the Honda Odyssey minivan, and can now be found on the Honda Accord Hybrid, the 2006 Honda Pilot, and the 2008 Honda Accord. Example: EPA estimates for the 2011 (271hp SOHC 3.5L) V6 Accord are 24mpg combined vs. 27 in the two 4 cylinder equipped models.

i-VTEC VCM was also used in 1.3L 4-cylinder engines used in Honda Civic Hybrid.

i-VTEC i

It is a version of i-VTEC with direct injection.

It was first used in 2003 Honda Stream.

AVTEC

The AVTEC (Advanced VTEC) engine was first announced in 2006. It combines continuously variable valve lift and timing control with continuously variable phase control. Honda originally planned to produce vehicles with AVTEC engines within next 3 years.

Although it was speculated that it would first be used in 2008 Honda Accord, the vehicle instead utilizes the existing i-VTEC system.

A related US patent (6,968,819) was filed in 2005-01-05.

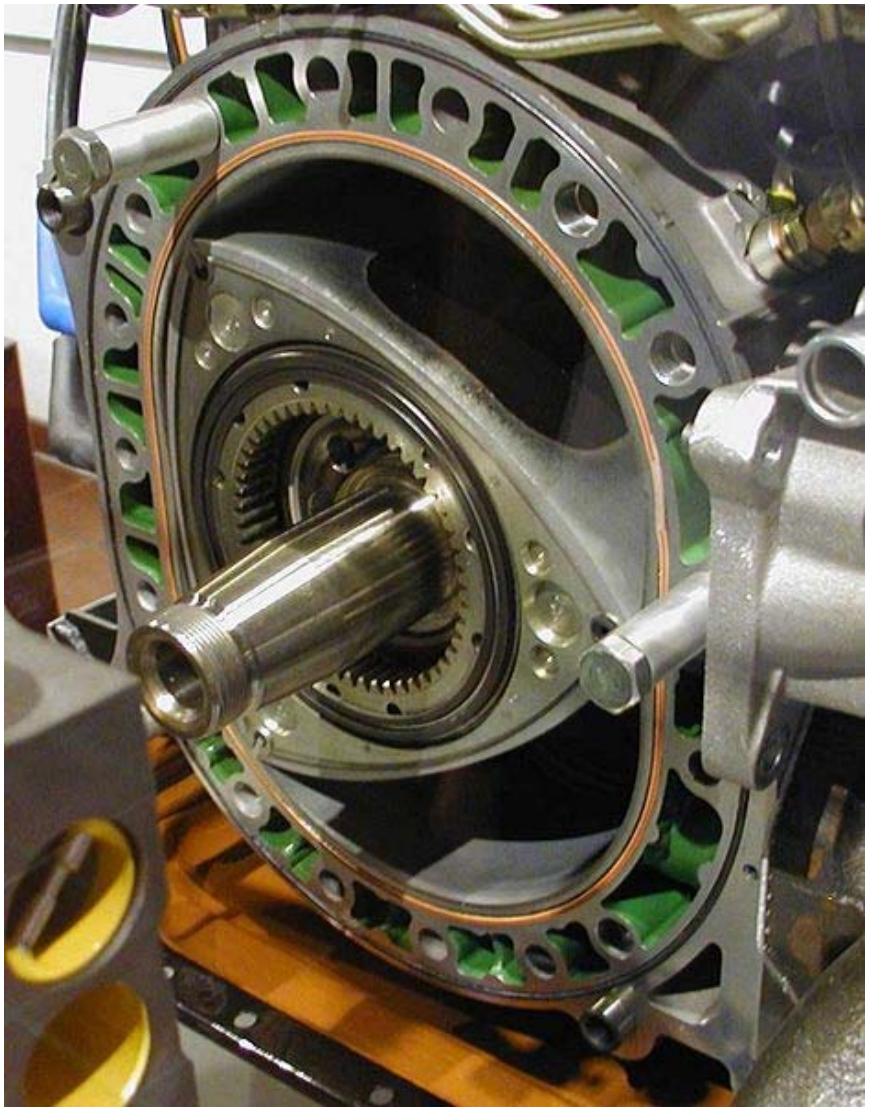
VTEC in motorcycles

Apart from the Japanese market-only Honda CB400SF Super Four HYPER VTEC, introduced in 1983, the first worldwide implementation of VTEC technology in a motorcycle occurred with the introduction of Honda's VFR800 sportbike in 2002. Similar to the SOHC VTEC-E style, one intake valve remains closed until a threshold of 7000 rpm is reached, then the second valve is opened by an oil-pressure actuated pin. The dwell of the valves remains unchanged, as in the automobile VTEC-E, and little extra power is produced but with a smoothing-out of the torque curve. Critics maintain that VTEC adds little to the VFR experience while increasing the engine's complexity. Honda seem to agree: their VFR1200, a model announced in October 2009 to replace the

VFR800, abandons the V-TEC concept in favour of a large capacity narrow-vee "unicam" (i.e. sohc) motor.

Chapter 7

Wankel Engine



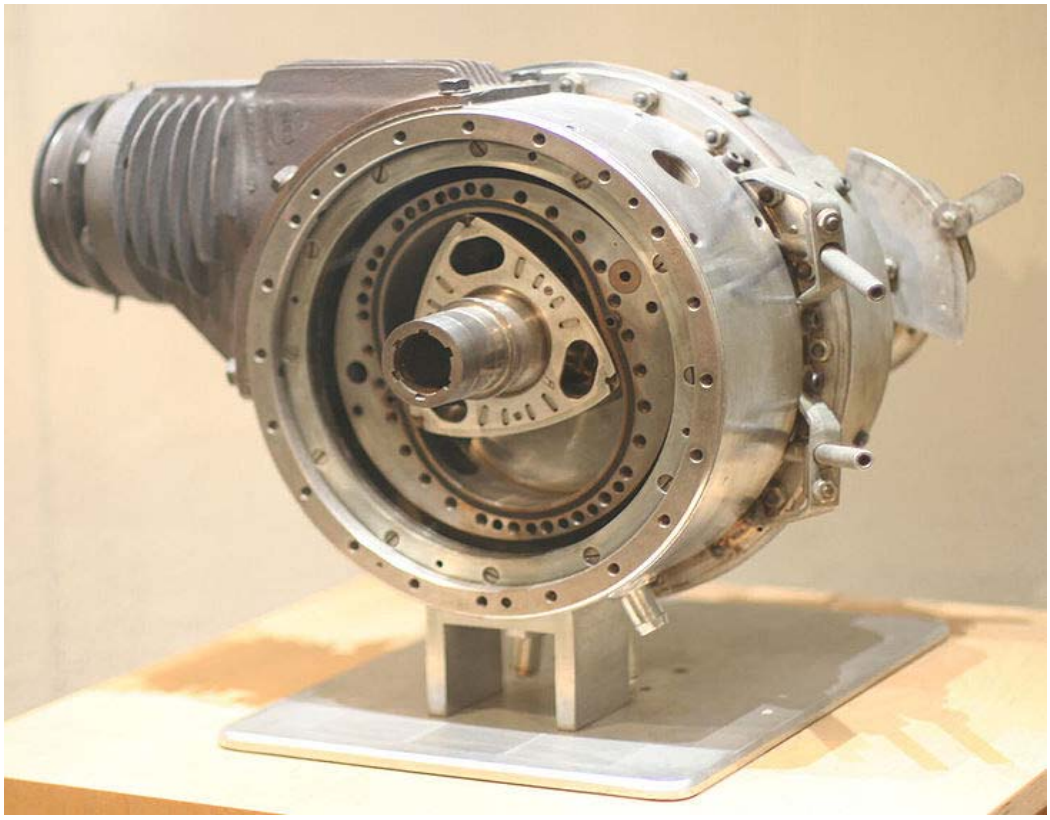
A Wankel engine in Deutsches Museum in Munich, Germany

The **Wankel engine** is a type of internal combustion engine that uses a rotary design to convert pressure into a rotating motion instead of using reciprocating pistons. Its four-stroke cycle takes place in a space between the inside of an oval-like epitrochoid-shaped housing and a rotor that is similar in shape to a Reuleaux triangle but with sides that are somewhat flatter. This design delivers smooth high-rpm power from a compact size. It is the only internal combustion engine invented in the twentieth century to go into production. Since its introduction the engine has been commonly referred to as the **rotary engine**, though this name is also applied to several completely different designs.

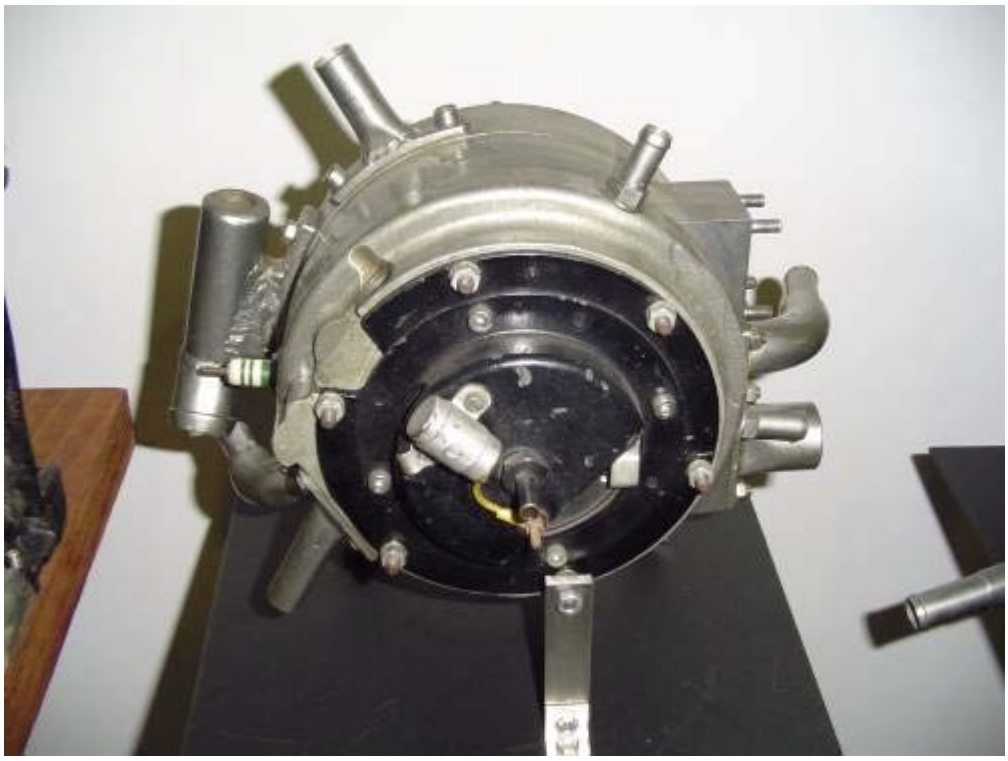
The engine was invented by German engineer Felix Wankel. He received his first patent for the engine in 1929, began development in the early 1950s at NSU Motorenwerke AG (NSU), and completed a working prototype in 1957. NSU then licensed the concept to companies around the world, which have continued to improve the design.

Because of their compact design, Wankel rotary engines have been installed in a variety of vehicles and devices such as automobiles (including racing cars), along with aircraft, go-karts, personal water craft, chain saws, and auxiliary power units. The most extensive automotive use of the Wankel engine has been by the Japanese company Mazda.

History



First DKM Wankel Engine DKM 54 (*Drehkolbenmotor*), at the Deutsches Museum in Bonn, Germany



First KKM Wankel Engine NSU KKM 57P (*Kreiskolbenmotor*), at Autovision und Forum, Germany

In 1951, the German engineer Felix Wankel began development of the engine at NSU Motorenwerke AG, where he first conceived his rotary engine in 1954 (DKM 54, *Drehkolbenmotor*). The so-called KKM 57 (the Wankel rotary engine, *Kreiskolbenmotor*) was constructed by NSU engineer Hanns Dieter Paschke in 1957 without the knowledge of Felix Wankel, who remarked "*you've turned my race horse into a plow mare*". The first working prototype DKM 54 was running on February 1, 1957 at the NSU research and development department *Versuchsabteilung TX*. It produced 21 horsepower; unlike modern Wankel engines, both the rotor and the housing rotated.

Considerable effort went into designing rotary engines in the 1950s and 1960s. They were of particular interest because they were smooth and quiet running, and because of the reliability resulting from their simplicity. An early problem of buildup of cracks in the epitrochoid surface was solved by installing the spark plugs in a separate metal piece instead of screwing them directly into the block.

Among the manufacturers signing licensing agreements to develop Wankel engines were Alfa Romeo, American Motors, Citroen, Ford, General Motors, Mercedes-Benz, Nissan, Porsche, Rolls-Royce, Suzuki, and Toyota. In the United States, in 1959 under license from NSU, Curtiss-Wright pioneered minor improvements in the basic engine design. In Britain, in the 1960s, Rolls Royce Motor Car Division pioneered a two-stage diesel version of the Wankel engine.

Also in Britain, Norton Motorcycles developed a Wankel rotary engine for motorcycles, based on the Sachs air cooled Wankel that powered the DKW/Hercules W-2000 motorcycle, which was included in their Commander and F1; Suzuki also made a production motorcycle with a Wankel engine, the RE-5, where they used ferrotic alloy apex seals and an NSU rotor in a successful attempt to prolong the engine's life. In 1971 and 1972 Arctic Cat produced snowmobiles powered by 303 cc Wankel rotary engines manufactured by Sachs in Germany. Deere & Company designed a version that was capable of using a variety of fuels. The design was proposed as the power source for United States Marine Corps combat vehicles and other equipment in the late 1980s.

Mazda and NSU signed a study contract to develop the Wankel engine in 1961 and competed to bring the first Wankel powered automobile to market. Although Mazda produced an experimental Wankel that year, NSU was first with a Wankel automobile on sale, the sporty NSU Spider in 1964; Mazda countered with a display of two and four rotor Wankel engines at that year's Tokyo Motor Show. In 1967, NSU began production of a Wankel engined luxury car, the Ro 80. However, problems with apex seal wear led to frequent engine failure, which led to large warranty costs for NSU, and curtailed further Wankel engine development.

Mazda's first Wankel engine, at the Mazda Museum in Hiroshima, Japan

Mazda, however, claimed to have solved the apex seal problem, and was able to run test engines at high speed for 300 hours without failure. After years of development, Mazda's first Wankel engine car was the 1967 Cosmo 110S. The company followed with a number of Wankel ("rotary" in the company's terminology) vehicles, including a bus and a pickup truck. Customers often cited the cars' smoothness of operation. However, Mazda chose a method to comply with hydrocarbon emission standards that, while less expensive to produce, increased fuel consumption, just before a sharp rise in fuel prices. Mazda later abandoned the Wankel in most of their automotive designs, but continued using it in their RX-7 sports car until August 2002 (RX-7 importation for Canada ceased with only the 1993 year being sold. The USA ended with the 1994 model year with remaining unsold stock being carried over as the '1995' year.). The company normally used two-rotor designs, but the 1991 Eunos Cosmo used a twin-turbo three-rotor engine. In 2003, Mazda introduced the Renesis engine with the RX-8. The Renesis engine relocated the ports for exhaust and intake from the periphery of the rotary housing to the sides, allowing for larger overall ports, better airflow, and further power gains. Early Wankel engines had also side intake and exhaust ports, but the concept was abandoned because of carbon buildup in ports and side of rotor. The Renesis engine solved the problem by using a keystone scraper side seal. The Renesis is capable of delivering 238 hp (177 kW) with better fuel economy, reliability, and environmental friendliness than previous Mazda rotary engines, all from its 1.3 L displacement.

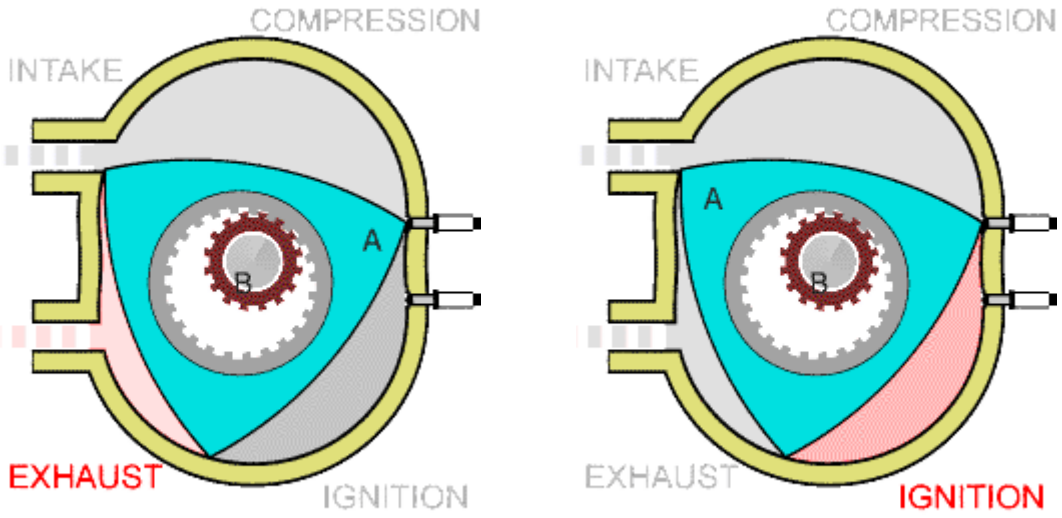
In 1961, the Soviet research organization of NATI, NAMI and VNIImotoprom started experimental development, and created experimental engines with different technologies.

Soviet automobile manufacturer AvtoVAZ also experimented with the use of Wankel engines in cars but without the benefit of a license. In 1974 they created a special engine design bureau, which in 1978 designed an engine designated as VAZ-311. In 1980, the company started delivering Wankel-powered VAZ-2106s (VAZ-411 engine with two-rotors) and Ladas, mostly to security services, of which about 200 were made. The next models were the VAZ-4132 and VAZ-415. Aviadvigatel, the Soviet aircraft engine design bureau, is known to have produced Wankel engines with electronic injection for aircraft and helicopters, though little specific information has surfaced.

Although many manufacturers licensed the design, including Citroën with their M35 and GS Birotor, using engines produced by Comotor, General Motors, which seems to have concluded that the Wankel engine was slightly more expensive to build than an equivalent reciprocating engine, and Mercedes-Benz which used it for their C111 concept car, only Mazda has produced Wankel engines in large numbers. American Motors (AMC) was so convinced "...that the rotary engine will play an important role as a powerplant for cars and trucks of the future...", according to Chairman Roy D. Chapin Jr., that the smallest U.S. automaker signed an agreement in February 1973, after a year's negotiations, to build Wankels for both passenger cars and Jeeps, as well as the right to sell any rotary engines it produces to other companies. It even designed the unique Pacer around the engine, even though by then, AMC had decided to buy the Wankel engines from GM instead of building them itself. However, GM's engines had not reached production when the Pacer was to hit the showrooms. Part of the demise of this feature

was the 1973 oil crisis with rising fuel prices, and also concerns about proposed US emission standards legislation. General Motors' Wankel did not comply with those emission standards, so in 1974 the company canceled its development, although GM claimed having solved the fuel consumption problem; unfortunately, they never published the results of their research. This meant the Pacer had to be reconfigured to house AMC's venerable AMC Straight-6 engine with rear-wheel drive

Design



The Wankel cycle. The "A" marks one of the three apexes of the rotor. The "B" marks the eccentric shaft and the white portion is the lobe of the eccentric shaft. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

In the Wankel engine, the four strokes of a typical Otto cycle occur in the space between a three-sided symmetric rotor and the inside of a housing, although the Wankel cycle differs from Otto cycle in the duration of the expansion part of cycle, that is much longer. In the basic single-rotor Wankel engine, the oval-like epitrochoid-shaped housing surrounds a rotor which is triangular with bow-shaped flanks (often confused with a Reuleaux triangle, a three-pointed curve of constant width, but with the bulge in the middle of each side a bit more flattened). The theoretical shape of the rotor between the fixed corners is the result of a minimization of the volume of the geometric combustion chamber and a maximization of the compression ratio, respectively. The symmetric curve connecting two arbitrary apexes of the rotor is maximized in the direction of the inner housing shape with the constraint not to touch the housing at any angle of rotation (an arc is not a solution of this optimization problem).

The central drive shaft, called the eccentric shaft or E-shaft, passes through the center of the rotor and is supported by fixed bearings. The rotors ride on eccentrics (analogous to

cranks) integral with the eccentric shaft (analogous to a crankshaft). The rotors both rotate around the eccentrics and make orbital revolutions around the eccentric shaft. Seals at the corners of the rotor seal against the periphery of the housing, dividing it into three moving combustion chambers. The rotation of each rotor on its own axis is caused and controlled by a pair of synchronizing gears A fixed gear mounted on one side of the rotor housing engages a ring gear attached to the rotor and ensures the rotor moves exactly 1/3 turn for each turn of the eccentric shaft. The power output of the engine is not transmitted through the synchronizing gears. The force of gas pressure on the rotor (to a first approximation) goes directly to the center of the eccentric, part of the output shaft.

The best way to visualize the action of the engine in the animation at left is to look not at the rotor itself, but the cavity created between it and the housing. The Wankel engine is actually a variable-volume progressing-cavity system. Thus there are 3 cavities per housing, all repeating the same cycle. Note as well that points A and B on the rotor and e-shaft turn at different speed, point B moves 3 times faster than point A, so that one full orbit of the rotor equates to 3 turns of the e-shaft.

As the rotor rotates and orbitally revolves, each side of the rotor gets closer and farther from the wall of the housing, compressing and expanding the combustion chamber similarly to the strokes of a piston in a reciprocating engine. The power vector of the combustion stage goes through the center of the offset lobe.

While a four-stroke piston engine makes one combustion stroke per cylinder for every two rotations of the crankshaft (that is, one-half power stroke per crankshaft rotation per cylinder), each combustion chamber in the Wankel generates one combustion stroke per each driveshaft rotation, i.e. one power stroke per rotor orbital revolution and three power strokes per rotor rotation. Thus, power output of a Wankel engine is generally higher than that of a four-stroke piston engine of similar engine displacement in a similar state of tune; and higher than that of a four-stroke piston engine of similar physical dimensions and weight.

Wankel engines also generally have a much higher redline than a reciprocating engine of similar power output, in part because the smoothness inherent in circular motion, but especially because they do not have highly stressed parts such as a crankshaft or connecting rods. Eccentric shafts do not have the stress-raising internal corners of crankshafts. The redline of a rotary engine is limited by wear of the synchronizing gears. Hardened steel gears are used for extended operation above 7000 or 8000 rpm. Mazda Wankel engines in auto racing are operated above 10,000 rpm. In aircraft they are used conservatively, up to 6500 or 7500 rpm. However, as gas pressure participates in seal efficiency, running a Wankel engine at high rpm under no load conditions can destroy the engine.

National agencies that tax automobiles according to displacement and regulatory bodies in automobile racing variously consider the Wankel engine to be equivalent to a four-stroke engine of 1.5 to 2 times the displacement; some racing series ban it altogether.

Engineering

Apex seals, left NSU Ro80 Serie and Research and right Mazda 12A and 13B

Left Mazda old L10A Camber axial cooling, middle Audi NSU EA871 axial water cooling only hot bow, right Diamond Engines Wankel radial cooling only in the hot bow

Felix Wankel managed to overcome most of the problems that made previous rotary engines fail by developing a configuration with vane seals that could be made of more durable materials than piston ring metal that led to the failure of previous rotary designs.

Rotary engines have a thermodynamic problem not found in reciprocating four-stroke engines in that their "cylinder block" operates at steady state, with intake, compression, combustion, and exhaust occurring at fixed housing locations for all "cylinders". In contrast, reciprocating engines perform these four strokes in one chamber, so that extremes of "freezing" intake and "flaming" exhaust are averaged and shielded by a boundary layer from overheating working parts.

The boundary layer shields and the oil film act as thermal insulation, leading to a low temperature of the lubricating film (max. ~200 °C/400 °F) on a water-cooled Wankel engine. This gives a more constant surface temperature. The temperature around the spark plug is about the same as the temperature in the combustion chamber of a reciprocating engine. With circumferential or axial flow cooling, the temperature difference remains tolerable.

Four-stroke reciprocating engines are less suitable for hydrogen. The hydrogen can misfire on hot parts like the exhaust valve and spark plugs. Another problem concerns the hydrogenate attack on the lubricating film in reciprocating engines. In a Wankel engine, this problem is circumvented by using a ceramic apex seal against a ceramic surface: there is no oil film to suffer hydrogenate attack. Since ceramic piston rings are not

available as of 2009, the problem remains with the reciprocating engine. The piston shell must be lubricated and cooled with oil. This substantially increases the lubricating oil consumption in a four-stroke hydrogen engine.

Materials

Unlike a piston engine, where the cylinder is cooled by the incoming charge after being heated by combustion, Wankel rotor housings are constantly heated on one side and cooled on the other, leading to high local temperatures and unequal thermal expansion. While this places high demands on the materials used, the simplicity of the Wankel makes it easier to use alternative materials like exotic alloys and ceramics. With water cooling in a radial or axial flow direction, with the hot water from the hot bow heating the cold bow, the thermal expansion remains tolerable.

Sealing

Early engine designs had a high incidence of sealing loss, both between the rotor and the housing and also between the various pieces making up the housing. Also, in earlier model Wankel engines carbon particles could become trapped between the seal and the casing, jamming the engine and requiring a partial rebuild. It was common for very early Mazda engines to require rebuilding after 50,000 miles (80,000 km). Further sealing problems arise from the uneven thermal distribution within the housings causing distortion and loss of sealing and compression. This thermal distortion also causes uneven wear between the apex seal and the rotor housing, quite evident on higher mileage engines. The problem is exacerbated when the engine is stressed before reaching operating temperature. However, Mazda Wankel engines have solved these problems. Current engines have nearly 100 seal-related parts.

Fuel consumption and emissions

Just as the shape of the Wankel combustion chamber is resistant to preignition and will run on lower-octane rating gasoline than a comparable piston engine, it also leads to relatively incomplete combustion of the air-fuel charge, with a larger amount of unburned hydrocarbons released into the exhaust. The exhaust is, however, relatively low in NOx emissions; this allowed Mazda to meet the United States Clean Air Act of 1970 in 1973 with a simple and inexpensive 'thermal reactor' (an enlarged open chamber in the exhaust manifold) by paradoxically enriching the air-fuel ratio to the point where the unburned hydrocarbons (HC) in the exhaust would support complete combustion in the thermal reactor; while piston-engine cars required expensive catalytic converters to deal with both unburned hydrocarbons and NOx emissions. This raised fuel consumption, however, (already a weak point for the Wankel engine) at the same time that the oil crisis of 1973 raised the price of gasoline. Mazda was able to improve the fuel efficiency of the thermal reactor system by 40% by the time of introduction of the RX-7 in 1978, but eventually shifted to the catalytic converter system. According to the Curtiss-Wright research, the extreme that controls the amount of unburned HC in the exhaust is the rotor surface temperature, higher temperatures producing less HC. They showed also that the rotor can

be widened. Quenching is the dominant source of HC at high speeds, and leakage at low speeds. The shape and positioning of rotor recess-combustion chamber- influences emissions and fuel use, the MDR being chosen as a compromise.

In Mazda's RX-8 with the Renesis engine, fuel consumption is now within normal limits while passing California State emissions requirements, including California's Low Emissions Vehicle or LEV standards. The exhaust ports, which in earlier Mazda rotaries were located in the rotor housings, were moved to the sides of the combustion chamber. This approach allowed Mazda to eliminate overlap between intake and exhaust port openings, while simultaneously increasing exhaust port area. The side port trapped the unburned fuel in the chamber decreased the oil consumption and improved the combustion stability in the low-speed and light load range. The HC emissions from the side exhaust port Wankel engine is 35 to 50 percent less than those from the peripheral exhaust port Wankel engine.

Advantages

NSU Wankel Spider, the first line of cars sold with a rotor Wankel engine

Mazda Cosmo, the first series two rotor Wankel engine sports car

Wankel engines are considerably simpler, lighter, and contain far fewer moving parts than piston engines of equivalent power output. For instance, because valving is accomplished by simple ports cut into the walls of the rotor housing, they have no valves or complex valve trains; in addition, since the rotor rides directly on a large bearing on the output shaft, there are no connecting rods and there is no crankshaft. The elimination of reciprocating mass and the elimination of the most highly stressed and failure prone parts of piston engines gives the Wankel engine high reliability, a smoother flow of power, and a high power-to-weight ratio.

The surface/volume-ratio problem is so complex that one cannot make a direct comparison between a reciprocating piston engine and a Wankel engine in terms of the surface/volume-ratio. The flow velocity and the heat losses behave quite differently. Surface temperatures behave absolutely differently; the film of oil in the Wankel engine acts as insulation. Engines with a higher compression ratio have a worse surface/volume-ratio. The surface/volume-ratio of a Diesel engine is much worse than a gasoline engine, but Diesel engines are well known for a higher efficiency factor than gasoline engines. Thus, engines with equal power should be compared: a naturally aspirated 1.3-liter Wankel engine with a naturally aspirated 1.3-liter four-stroke reciprocating piston engine with equal power. But such a four-stroke engine is not possible and needs twice the displacement for the same power as a Wankel engine. The extra or "empty" stroke(s)

should not be ignored, as a 4-stroke cylinder produces a power stroke only every other rotation of the crankshaft. In actuality, this doubles the real surface/volume-ratio for the four-stroke reciprocating piston engine and the demand of displacement. The Wankel, therefore, has higher volumetric efficiency and a lower pumping loss through the absence of choking valves. Because of the quasi-overlap of the power strokes that cause the smoothness of the engine and the avoidance of the 4-stroke cycle in a reciprocating engine, the Wankel engine is very quick to react to throttle changes and is able to quickly deliver a surge of power when the demand arises, especially at higher rpm. This difference is more pronounced when compared to four-cylinder reciprocating engines and less pronounced when compared to higher cylinder counts.

In addition to the removal of internal reciprocating stresses by virtue of the complete removal of reciprocating internal parts typically found in a piston engine, the Wankel engine is constructed with an iron rotor within a housing made of aluminium, which has a greater coefficient of thermal expansion. This ensures that even a severely overheated Wankel engine cannot seize, as would be likely to occur in an overheated piston engine. This is a substantial safety benefit of use in aircraft. In addition, valves and valve trains that don't exist can't burn out, jam, break, or malfunction in any way, again increasing safety.

A further advantage of the Wankel engine for use in aircraft is the fact that a Wankel engine generally has a smaller frontal area than a piston engine of equivalent power, allowing a more aerodynamic nose to be designed around it. The simplicity of design and smaller size of the Wankel engine also allows for savings in construction costs, compared to piston engines of comparable power output.

Wankel engines that operate within their original design parameters are almost immune to catastrophic failure. A Wankel engine that loses compression, cooling or oil pressure will lose a large amount of power, and will die over a short period of time; however, it will usually continue to produce some power during that time. Piston engines under the same circumstances are prone to seizing or breaking parts that almost certainly results in major internal damage of the engine and an instant loss of power. For this reason, Wankel engines are very well suited to snowmobiles and aircraft, which often take users into remote places where a failure could result in frostbite or death.

Due to a 50% longer stroke duration compared to a four-cycle engine, there is more time to complete the combustion. This leads to greater suitability for direct injection. A Wankel rotary engine has stronger flows of air-fuel mixture and a longer operating cycle than a reciprocating engine, so it realizes concomitantly thorough mixing of hydrogen and air. The result is a homogeneous mixture, which is crucial for hydrogen combustion.

Disadvantages

Rolls Royce R6 two stage Wankel Diesel engine

Although in two dimensions the seal system of a Wankel looks to be even simpler than that of a corresponding multi-cylinder piston engine, in three dimensions the opposite is true. As well as the rotor apex seals evident in the conceptual diagram, the rotor must also seal against the chamber ends.

Piston rings are not perfect seals: each has a gap to allow for expansion. The sealing at the Wankel apexes is less critical, as leakage is between adjacent chambers on adjacent strokes of the cycle, rather than to the crankcase. However, the less effective sealing of the Wankel is one factor reducing its efficiency, limiting its use mainly to applications such as racing engines and sports vehicles where neither efficiency nor long engine life are major considerations. Comparison tests have shown that the Mazda rotary powered RX-8 uses more fuel than a heavier vehicle powered by larger displacement V-8 engine for similar performance results.

The time available for fuel to be port-injected into a Wankel engine is significantly shorter, compared to four-stroke piston engines, due to the way the three chambers rotate. The fuel-air mixture cannot be pre-stored as there is no intake valve. Also the Wankel engine, compared to a piston engine, has 50% longer stroke duration. The four Otto cycles last 1080° for a Wankel engine versus 720° for a four-stroke reciprocating piston engine.

There are various methods of calculating the engine displacement of a Wankel. The Japanese regulations for calculating displacements for engine ratings use the volume displacement of one rotor face only, and the auto industry commonly accepts this method as the standard for calculating the displacement of a rotary. However, when compared on the basis of specific output, the convention results in large imbalances in favor of the Wankel motor.

For comparison purposes between a Wankel Rotary engine and a piston engine, displacement and corresponding power output can more accurately be compared on the basis of displacement per revolution of the eccentric shaft. A calculation of this form dictates that a two rotor Wankel displacing 654 cc per face will have a displacement of 1.3 liters per every rotation of the eccentric shaft (only two total faces, one face per rotor going through a full power stroke) and 2.6 liters after two revolutions (four total faces, two faces per rotor going through a full power stroke). The results are directly comparable to a 2.6-liter piston engine with an even number of cylinders in a conventional firing order, which will likewise displace 1.3 liters through its power stroke after one revolution of the crankshaft, and 2.6 liters through its power strokes after two revolutions of the crankshaft. A Wankel Rotary engine is still a 4-stroke engine and pumping losses from non-power strokes still apply, but the absence of throttling valves and a 50% longer stroke duration result in a significantly lower pumping loss compared against a four-stroke reciprocating piston engine. Measuring a Wankel rotary engine in this way more accurately explains its specific output, as the volume of its air fuel mixture put through a complete power stroke per revolution is directly responsible for torque and thus power produced.

The trailing side of the rotary engine's combustion chamber develops a squeeze stream which pushes back the flamefront. With the conventional two-spark-plug or one-spark-plug system and homogenous mixture, this squeeze stream prevents the flame from propagating to the combustion chamber's trailing side in the mid and high engine speed ranges. This is why there can be more carbon monoxide and unburnt hydrocarbons in a Wankel's exhaust stream. A side-port exhaust, as is used in the Renesis, avoids this because the unburned mixture cannot escape. The Mazda 26B avoided this issue through a 3-spark plug ignition system. (As a result, at the Le Mans 24 hour endurance race in 1991, the 26B had significantly lower fuel consumption than the competing reciprocating piston engines. All competitors had only the same amount of fuel available, because of the Le Mans 24 h limited fuel quantity rule.) A peripheral intake port gives the highest MEP, however, side intake porting produces a more steady idle.

All Mazda-made Wankel rotaries, including the new Renesis found in the RX-8, burn a small quantity of oil by design; it is metered into the combustion chamber to preserve the apex seals. Owners must periodically add small amounts of oil, marginally increasing running costs — though it is still reasonable and comparable in some instances when compared to many reciprocating piston engines.

Applications

Automobile racing

Mazda 787B

In the racing world, Mazda has had substantial success with two-rotor, three-rotor, and four-rotor cars. Private racers have also had considerable success with stock and modified Mazda Wankel-engine cars.

The Sigma MC74 powered by a Mazda 12A engine was the first engine and only team from outside Western Europe or the United States to finish the entire 24 hours of the 24 Hours of Le Mans race, in 1974. Mazda is the only team from outside Western Europe or the United States to have won Le Mans outright and the only non-piston engine ever to win Le Mans, which the company accomplished in 1991 with their four-rotor 787B (2,622 cc/160 cu in—actual displacement, rated by FIA formula at 4,708 cc/287 cu in). The following year, a planned rule change at Le Mans made the Mazda 787B ineligible to race anymore due to weight advantages.

The Mazda RX-7 has won more IMSA races in its class than any other model of automobile, with its one hundredth victory on September 2, 1990. Following that, the RX-7 won its class in the IMSA 24 Hours of Daytona race ten years in a row, starting in 1982. The RX7 won the IMSA Grand Touring Under Two Liter (GTU) championship each year from 1980 through 1987, inclusive.

Formula Mazda Racing features open-wheel race cars with Mazda Wankel engines, adaptable to both oval tracks and road courses, on several levels of competition. Since 1991, the professionally organized Star Mazda Series has been the most popular format for sponsors, spectators, and upward bound drivers. The engines are all built by one engine builder, certified to produce the prescribed power, and sealed to discourage tampering. They are in a relatively mild state of racing tune, so that they are extremely reliable and can go years between motor rebuilds.

The Malibu Grand Prix chain, similar in concept to commercial recreational kart racing tracks, operates several venues in the United States where a customer can purchase several laps around a track in a vehicle very similar to open wheel racing vehicles, but powered by a small Curtiss-Wright rotary engine.

In engines having more than two rotors, or two rotor race engines intended for high-rpm use, a multi-piece eccentric shaft may be used, allowing additional bearings between rotors. While this approach does increase the complexity of the eccentric shaft design, it has been used successfully in the Mazda's production three-rotor 20B-REW engine, as well as many low volume production race engines. (The C-111-2 4 Rotor Mercedes-Benz eccentric shaft for the KE Serie 70, Typ DB M950 KE409 is made in one piece. Mercedes-Benz used split bearings.)

Motorcycle engines

Norton Interpol2 prototype

From 1974 to 1977 Hercules produced a limited number of motorcycles powered by Wankel engines. The motor tooling and blank apex seals were later used by Norton to produce the Norton Commander model in the early 1980s.

The Suzuki RE5 was a Wankel-powered motorcycle produced in 1975 and 1976. It was touted as the future of motorcycling, however, other problems and a lack of parts interchangeability meant low sales.

Dutch motorcycle importer and manufacturer van Veen produced small quantities of their dual rotor Wankel-engined OCR-1000 between 1978 and 1980, using surplus Comotor engines.

However, from the 1980s onwards, rotary engines have not been produced for sale to the general public for road use. Norton has used a Wankel engine in several models including the F1, F1 Sports, RC588, RCW588, NRS588, most notably Steve Hislop riding to various victories on Norton's F1 in the TT in 1992. Norton now makes a 588cc twin-rotor model called the NRV588 and is in the process of making a 700cc version called the NRV700.

Aircraft engines

Diamond DA20 with Diamond Engines Wankel

Sikorsky Cypher UAV powered with a UEL AR801 Wankel engine

The first Wankel rotary-engine aircraft was the experimental Lockheed Q-Star civilian version of the United States Army's reconnaissance QT-2, basically a powered Schweizer sailplane, in 1968 or 1969. It was powered by a 185 hp (138 kW) Curtiss-Wright RC2-60 Wankel rotary engine.

Aircraft Wankels have made something of a comeback in recent years. None of their advantages have been lost in comparison to other engines. They are increasingly being found in roles where their compact size and quiet operation is important, notably in drones, or UAVs. Many companies and hobbyists adapt Mazda rotary engines (taken from automobiles) to aircraft use; others, including Wankel GmbH itself, manufacture Wankel rotary engines dedicated for the purpose. One such use are the "Rotapower" engines in the Moller Skycar M400.

Wankel engines are also becoming increasingly popular in homebuilt experimental aircraft. Most are Mazda 12A and 13B automobile engines, converted to aviation use. This is a very cost-effective alternative to certified aircraft engines, providing engines ranging from 100 to 300 horsepower (220 kW) at a fraction of the cost of traditional engines. These conversions first took place in the early 1970s. With a number of these engines mounted on aircraft, as of 10 December 2006 the National Transportation Safety Board has only seven reports of incidents involving aircraft with Mazda engines, and none of these were a failure due to design or manufacturing flaws.

Peter Garrison, Contributing Editor for *Flying* magazine, has said that "the most promising engine for aviation use is the Mazda rotary." Mazdas have indeed worked well when converted for use in homebuilt aircraft. However, the real challenge in aviation is

producing FAA-certified alternatives to the standard reciprocating engines that power most small general aviation aircraft. Mistral Engines, based in Switzerland, developed purpose-built rotaries for factory and retro-fit installations on certified production aircraft. The G-190 and G-230-TS rotary engines were already flying in the experimental market, and Mistral Engines hoped for FAA and JAA certification by 2011. As of June 2010, G-300 rotary engine development ceased, with the company citing a need for cash flow to complete development.

Mistral claims to have overcome the challenges of fuel consumption inherent in the rotary, at least to the extent that the engines are demonstrating specific fuel consumption within a few points of reciprocating engines of similar displacement. While fuel burn is still marginally higher than traditional engines, it is outweighed by other beneficial factors.

Since Wankel engines operate at a relatively high rotational speed with relatively low torque, propeller aircraft must use a Propeller Speed Reduction Unit (PSRU) to keep conventional propellers within the proper speed range. There are many experimental aircraft flying with this arrangement.

Pratt & Whitney Rocketdyne have been commissioned by DARPA to develop a diesel wankel engine for use in a prototype VTOL flying car called the "Transformer". The engine, based on an earlier UAV diesel wankel concept called 'EnduroCORE', will utilize wankel rotors of varying sizes on a shared eccentric shaft to increase efficiency. The engine is claimed to be a 'full-compression, full-expansion, diesel-cycle engine', which sets it apart from the earlier Rolls-Royce prototype that required an external air compressor to achieve high enough compression for diesel-cycle combustion.

Other uses

UEL UAV-741 Wankel engine for a UAV

Small Wankel engines are being found increasingly in other roles, such as go-karts, personal water craft and auxiliary power units for aircraft. The Graupner/O.S. 49-PI is a 1.27 hp (947 W) 5 cc Wankel engine for model airplane use which has been in production essentially unchanged since 1970; even with a large muffler, the entire package weighs only 380 grams (13.4 ounces).

The simplicity of the Wankel makes it well-suited for mini, micro, and micro-mini engine designs. The Microelectromechanical systems (MEMS) Rotary Engine Lab at the University of California, Berkeley has been developing Wankel engines of down to 1 mm in diameter with displacements less than 0.1 cc. Materials include silicon and motive power includes compressed air. The goal is to eventually develop an internal combustion engine that will deliver 100 milliwatts of electrical power; the engine itself will serve as the rotor of the generator, with magnets built into the engine rotor itself.

The largest Wankel engine was built by Ingersoll-Rand; available in 550 hp (410 kW) one rotor and 1,100 hp (820 kW) two rotor versions, displacing 41 liters per rotor with a

rotor approximately one meter in diameter, it was available between 1975 and 1985. It was derived from a previous, unsuccessful Curtiss-Wright design, which failed because of a well-known problem with all internal combustion engines: the fixed speed at which the flame front travels limits the distance combustion can travel from the point of ignition in a given time, and thereby limiting the maximum size of the cylinder or rotor chamber which can be used. This problem was solved by limiting the engine speed to only 1200 rpm and the use of natural gas as fuel; this was particularly well chosen, since one of the major uses of the engine was to drive compressors on natural gas pipelines. Yanmar Diesel of Japan, produced some small, charge cooled rotor rotary engines for uses such as chainsaws and outboard engines, some of their contributions are that the LDR (rotor recess in the leading edge of combustion chamber) engines had better exhaust emissions profiles, and that reed-valve controlled intake ports improve part-load and low RPM performance.(Kojiro Yamaoka & Hiroshi Tado, SAE paper 720466, 1972)

In 2010 Audi revealed that in their electric car the A1 e-tron they would have a small 250 cc Wankel engine running at 5,000 rpm that would recharge the car's batteries as needed.

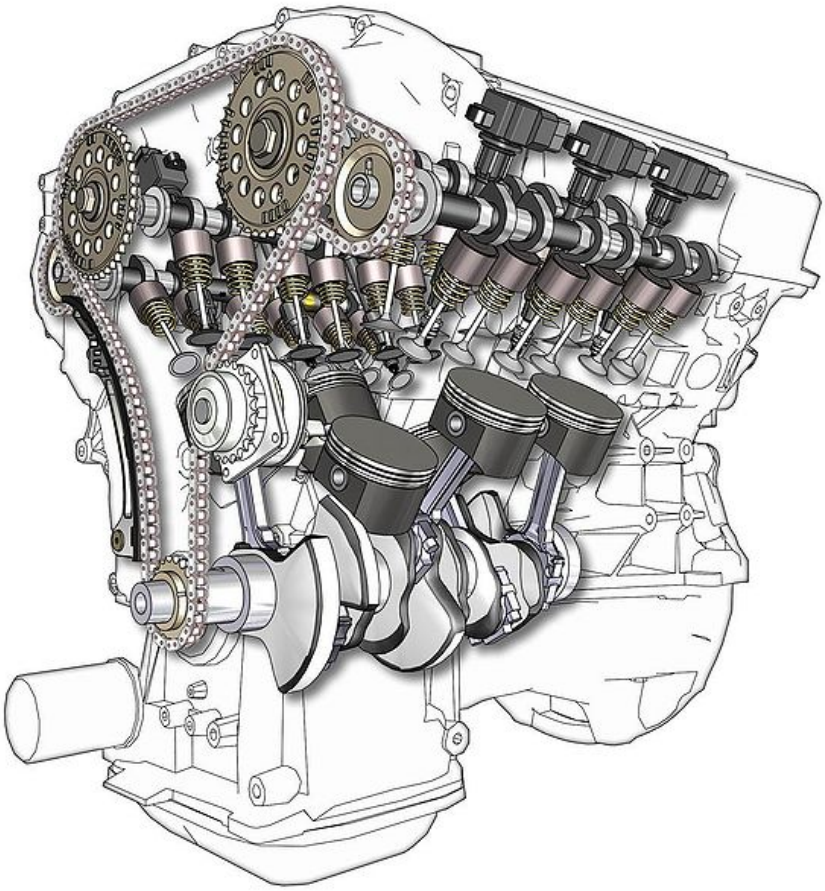
Non-internal combustion

In addition for use as an internal combustion engine, the basic Wankel design has also been utilized for gas compressors, and superchargers for internal combustion engines, but in these cases, although the design still offers advantages in reliability, the basic advantages of the Wankel in size and weight over the four-stroke internal combustion engine are irrelevant. In a design using a Wankel supercharger on a Wankel engine, the supercharger is twice the size of the engine.

The Wankel design is used in the seat belt pre-tensioner system of some Mercedes-Benz and Volkswagen cars. When the deceleration sensors sense a potential crash, small explosive cartridges are triggered electrically and the resulting pressurized gas feeds into tiny Wankel engines which rotate to take up the slack in the seat belt systems, anchoring the driver and passengers firmly in the seat before a collision.

Chapter 8

V6 Engine



A V6, 24-valve, DOHC engine

A **V6 engine** is a V engine with six cylinders mounted on the crankcase in two banks of three cylinders, usually set at either a right angle or an acute angle to each other, with all six pistons driving a common crankshaft. It is the second most common engine configuration in modern cars after the inline four.

The V6 is one of the most compact engine configurations, shorter than the straight 4 and in many designs narrower than the V8 engine, and is well suited to the popular transverse engine front-wheel drive layout. It is becoming more common as the space allowed for engines in modern cars is reduced at the same time as power requirements increase, and has largely replaced the inline-6, which is too long to fit in many modern engine compartments. Although it is more complicated and not as smooth as the inline 6, the V6 is more compact, more rigid, and less prone to torsional vibrations in the crankshaft. The V6 engine has become widely adopted for medium-sized cars, often as an optional engine where a straight-4 is standard, or as a base engine where a V8 is a higher-cost performance option.

Recent V6 engines have delivered horsepower and torque output comparable to contemporary V8 engines, while reducing fuel consumption and emissions, such as the Volkswagen Group's G60 3.0 TFSI which is supercharged and directly injected, and Ford Motor Company's turbocharged and directly injected EcoBoost V6, both of which have been compared to Volkswagen's 4.2 V8 engine.

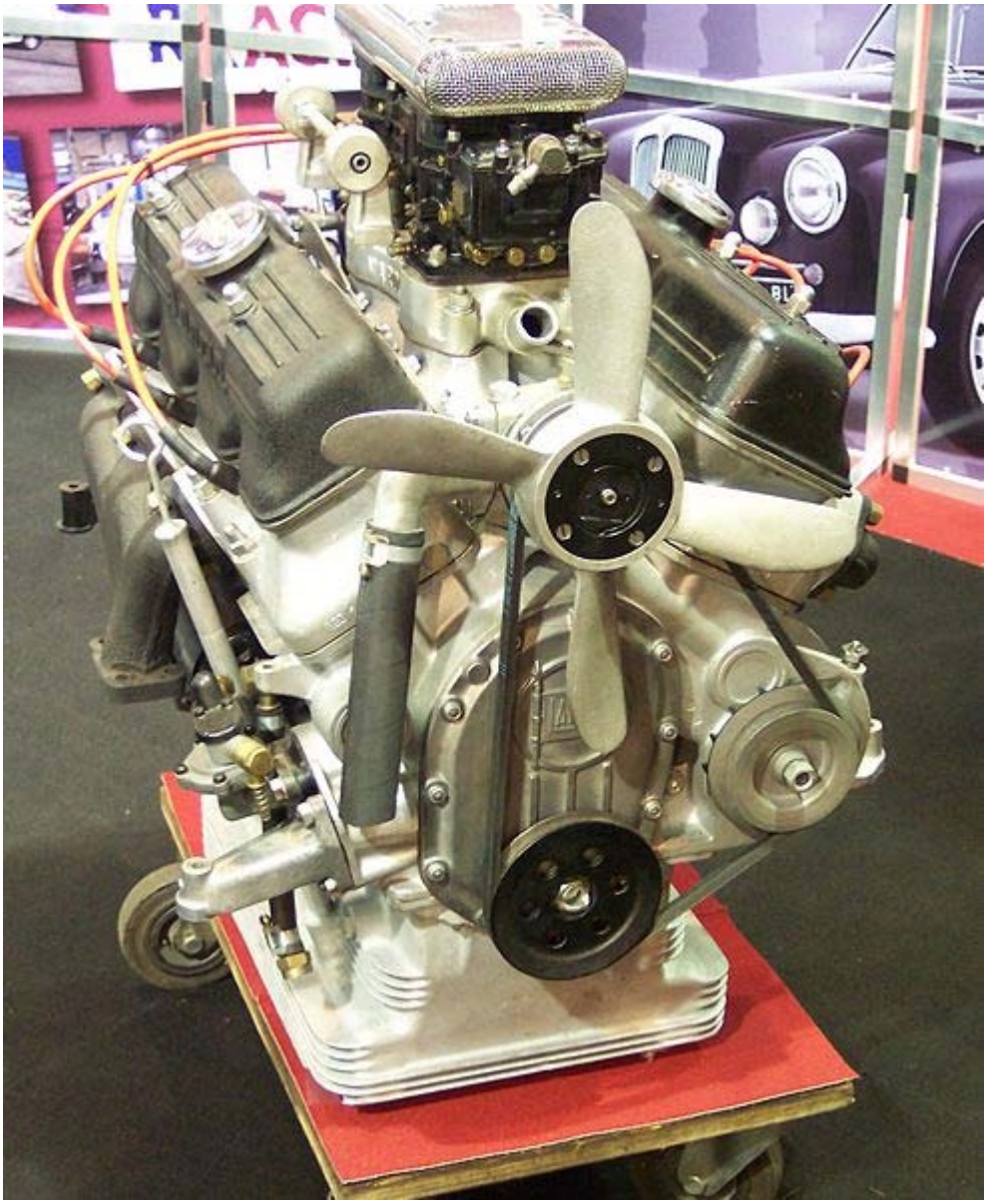
Modern V6 engines commonly range in displacement from 2.5 to 4.3 L (150 to 260 cu in), though larger and smaller examples have been produced.

History

Some of the first V6-cars were built in 1905 by Marmon. Marmon was something of a V-Specialist which began with V2-engines, then built V4's and V6's, later V8's and in the 30's Marmon was one of the few car-makers of the world which ever built a V16 car.

From 1908-1913 the Deutz Gasmotoren Fabrik produced benzene electric trainsets (Hybrid) which used a V6 as generator-engine.

Another V6-car was designed in 1918 by Leo Goosen for Buick Chief Engineer Walter L. Marr. Only one prototype Buick V6 car was built in 1918 and was long used by the Marr family.



Lancia V6

The first series production V6 was introduced by Lancia in 1950 with the Lancia Aurelia. Other manufacturers took note and soon other V6 engines were in use. In 1959, GM introduced a heavy-duty 305 in³ (5 L) 60° V6 for use in their pickup trucks and Suburbans, an engine design that was later enlarged to 478 in³ (7.8 L) for heavy truck and bus use.

1962 saw the introduction of the Buick Special, which offered a 90° V6 with uneven firing intervals that shared some parts commonality with a small Buick V8 of the period. Consequently the Buick Special met consumer resistance due to its excessive vibration. In 1983, Nissan produced Japan's first V6 engine with the VG series.

Balance and smoothness

Due to the odd number of cylinders in each bank, V6 designs are inherently unbalanced, regardless of their V-angle. All straight engines with an odd number of cylinders suffer from primary dynamic imbalance, which causes an end-to-end rocking motion. Each cylinder bank in a V6 has an odd number of pistons, so the V6 also suffers from the same problem unless steps are taken to mitigate it. In the horizontally-opposed flat-6 layout, the rocking motions of the two straight cylinder banks offset each other, while in the inline-6 layout, the two ends of engine are mirror images of each other and compensate every rocking motion. Concentrating on the first order rocking motion, the V6 can be assumed to consist of two separate straight-3 where counterweights on the crankshaft and a counter rotating balancer shaft compensate the first order rocking motion. At mating, the angle between the banks and the angle between the crankshafts can be varied so that the balancer shafts cancel each other 90° V6 (larger counter weights) and the even firing 60° V6 with 60° flying arms (smaller counter weights. The second order rocking motion can be balanced by a single co-rotating balancer shaft.).

This is almost the same technique which balances an even firing 90° crossplane V8 in primary and secondary order. A 90° V8 is in primary balance because each 4-cylinder bank is in primary balance, and the secondary of the two banks can be made to cancel each other using a crossplane. However, there is no equivalent of the crossplane crankshaft for the V6, so that the vibrations from the two banks cannot be made to completely cancel each other. This makes designing a smooth V6 engine a much more complicated problem than the straight-6, flat-6, and V8 layouts. Although the use of offset crankpins, counterweights, and flying arms has reduced the problem to a minor second-order vibration in modern designs, all V6s can benefit from the addition of auxiliary balance shafts to make them completely smooth.

When Lancia pioneered the V6 in 1950, they used a 60° angle between the cylinder banks and a six-throw crankshaft to achieve equally spaced firing intervals of 120°. This still has some balance and secondary vibration problems. When Buick designed a 90° V6 based on their 90° V8, they initially used a simpler three-throw crankshaft laid out in the same manner as the V8 with pairs of connecting rods sharing the same crankpin, which resulted in firing intervals alternating between 90° and 150°. This produced a rough-running design which was unacceptable to many customers. Later, Buick and other manufacturers refined the design by using a *split-pin* crankshaft which achieved a regular 120° firing interval by staggering adjacent crankpins by 15° in opposite directions to eliminate the uneven firing and make the engine reasonably smooth. Some manufacturers such as Buick in later versions of their V6 and Mercedes Benz have taken the 90° design a step further by adding a balancing shaft to offset the primary vibrations and produce an almost fully balanced engine.

Some designers have reverted to a 60° angle between cylinder banks, which produces a more compact engine, but have used three-throw crankshafts with *flying arms* between the crankpins of each throw to achieve even 120° angles between firing intervals. This has the additional advantage that the flying arms can be weighted for balancing purposes.

This still leaves an unbalanced primary couple, which is offset by counterweights on the crankshaft and flywheel to leave a small secondary couple, which can be absorbed by carefully designed engine mounts.

Six-cylinder designs are also more suitable for larger displacement engines than four-cylinder ones because power strokes of pistons overlap. In a four-cylinder engine, only one piston is on a power stroke at any given time. Each piston comes to a complete stop and reverses direction before the next one starts its power stroke, which results in a gap between power strokes and noticeable vibrations. In a six-cylinder engine (other than odd-firing V6s), the next piston starts its power stroke 60° before the previous one finishes, which results in smoother delivery of power to the flywheel. In addition, because inertial forces are proportional to piston displacement, high-speed six-cylinder engines will suffer less stress and vibration per piston than an equal displacement engine with fewer cylinders.

Comparing engines on the dynamometer, a typical even-fire V6 shows instantaneous torque peaks of 150% above mean torque and valleys of 125% below mean torque, with a small amount of negative torque (engine torque reversals) between power strokes. On the other hand, a typical four-cylinder engine shows peaks of nearly 300% above mean torque and valleys of 200% below mean torque, with 100% negative torque being delivered between strokes. In contrast, a V8 engine shows peaks of less than 100% above and valleys of less than 100% below mean torque, and torque never goes negative. The even-fire V6 thus ranks between the four and the V8, but closer to the V8, in smoothness of power delivery. An odd-fire V6, on the other hand, shows highly irregular torque variations of 200% above and 175% below mean torque, which is significantly worse than an even-fire V6, and in addition the power delivery shows large harmonic vibrations that have been known to destroy the dynamometer.

V angles

60 degrees

Nissan VG30E engine

The most efficient cylinder bank angle for a V6 is 60 degrees, minimizing size and vibration. While 60° V6 engines are not as well balanced as inline-6 and flat-6 engines, modern techniques for designing and mounting engines have largely disguised their vibrations. Unlike most other angles, 60 degree V6 engines can be made acceptably smooth without the need for balance shafts. When Lancia pioneered the 60° V6 in 1950, a 6-throw crankshaft was used to give equal firing intervals of 120°. However, more modern designs often use a 3-throw crankshaft with what are termed *flying arms* between the crankpins, which not only give the required 120° separation but also can be used for balancing purposes. Combined with a pair of heavy counterweights on the crankshaft ends, these can eliminate all but a modest secondary imbalance which can easily be damped out by the engine mounts.

This configuration is a good fit in cars which are too big to be powered by four-cylinder engines, but for which compactness and low cost are important. The most common 60° V6s were built by General Motors (the heavy duty commercial models, as well as a design used in many GM front wheel drive cars) and Ford European subsidiaries (Essex V6, Cologne V6 and the more recent Duratec V6). Other 60° V6 engines are the Chrysler

3.3 V6 engine, the Nissan VQ engine, the Alfa Romeo V6 engine, and later versions of the Mercedes-Benz V6 engine.

90 degrees

90° V6 engines are also produced, usually so they can use the same production-line tooling set up to produce V8 engines (which normally have a 90° V angle). Although it is relatively easy to derive a 90° V6 from an existing V8 design by simply cutting two cylinders off the engine, this tends to make it wider and more vibration-prone than a 60° V6. The design was first used by Buick when it introduced its 198 CID *Fireball V6* as the standard engine in the 1962 Special. Other examples include the Maserati V6 used in the Citroën SM, the PRV V6, Chevrolet's 4.3 L *Vortec 4300* and Chrysler's 3.9 L (238 in³) *Magnum V6* and 3.7 L (226 in³) *PowerTech V6*. The Buick V6 was notable because it introduced the concept of uneven firing, as a result of using the 90° V8 cylinder angle without adjusting the crankshaft design for the V6 configuration. Rather than firing every 120° of crankshaft rotation, the cylinders would fire alternately at 90° and 150°, resulting in strong harmonic vibrations at certain engine speeds. These engines were often referred to by mechanics as "shakers", due to the tendency of the engine to bounce around at idle speed.

More modern 90° V6 engine designs avoid these vibration problems by using crankshafts with offset split crankpins to make the firing intervals even, and often add balancing shafts to eliminate the other vibration problems. Examples include the later versions of the Buick V6, and earlier versions of the Mercedes-Benz V6. The Mercedes V6, although designed to be built on the same assembly lines as the V8, used split crankpins, a counter-rotating balancing shaft, and careful acoustic design to make it almost as smooth as the inline-6 it replaced. However, in later versions Mercedes changed to a 60° angle, making the engine more compact and allowing elimination of the balancing shaft. Despite the difference in V angles, the Mercedes 60° V6s were built on the same assembly lines as 90° V8s.

120 degrees

120° might be described as the *natural* angle for a V6 since the cylinders fire every 120° of crankshaft rotation. Unlike the 60° or 90° configuration, it allows pairs of pistons to share crank pins in a three-throw crankshaft without requiring flying arms or split crankpins to be even-firing. However, unlike the crossplane crankshaft V8, there is no way to arrange a V6 so that unbalanced forces from the two cylinder banks will completely cancel each other. As a result, the 120° V6 acts like two straight-3s running on the same crankshaft and, like the straight-3, suffers from a primary dynamic imbalance which requires a balance shaft to offset.

The 120° layout also produces an engine which is too wide for most automobile engine compartments, so it is more often used in racing cars where the car is designed around the engine rather than vice-versa, and vibration is not as important. By comparison, the 180° flat-6 *boxer* engine is only moderately wider than the 120° V6, and unlike the V6 is a

fully-balanced configuration with no vibration problems, so it is more commonly used in aircraft and in sports/luxury cars where space is not a constraint and smoothness is important.

Spanish truck manufacturer Pegaso built the first production 120° V6 for the Z-207 mid size truck in 1955. The engine, a 7.5 litre alloy Diesel designed under the direction of engineer Wifredo Ricart uses a single balance shaft rotating at the speed of the crankshaft

Ferrari introduced a very successful 120° V6 racing engine in 1961. The Ferrari Dino 156 engine was shorter and lighter than the 65° Ferrari V6 engines that preceded it, and the simplicity and low center of gravity of the engine was an advantage in racing. It won a large number of Formula One races between 1961 and 1964. However, Enzo Ferrari had a personal dislike of the 120° V6 layout, preferring a 65° angle, and after that time it was replaced by other engines.

Bombardier designed 120° V220/V300T V6 engines for use in light aircraft. The ignition sequence was symmetrical, with each cylinder firing 120° after the previous cylinder resulting in smooth power delivery. A balance shaft on the bottom of the engine offset the primary dynamic imbalance. The straight, pin-type crankshaft journals in the 120° V-6 layout allowed a shorter and stiffer crankshaft than competing flat-6 engines, while water cooling resulted in better temperature control than air cooling. These engines could run on automotive gasoline rather than avgas. However, the design was shelved in 2006 and there are no plans for production.

Other angles

Narrower angle V6 engines are very compact but can suffer from severe vibration problems unless very carefully designed. Notable V6 bank angles include:

- The 10.6° and 15° Volkswagen VR6, which is such a narrow angle it can use a single cylinder head and double overhead camshafts for both cylinder banks. With seven main bearings, it is more like a staggered-bank in-line six rather than a normal V6, but is only slightly longer and wider than a straight-4.
- The 45° Electro-Motive 6 cylinder version of their model 567 Diesel locomotive engine. This angle is optimum for the more common 16 cylinder version.
- The 54° GM/Opel V6, designed to be narrower than normal for use in small front-wheel drive cars.
- The 65° Ferrari Dino V6, allowing larger carburetors (for potentially higher power in race tuning) than a 60° angle, while suffering a slight increase in vibrations.
- The 75° Isuzu Rodeo and Isuzu Trooper V6 of 3.2 and 3.5 L in both SOHC and DOHC versions.
- The 80° Honda RA168-E Formula One engine in the McLaren MP4/4.

Odd and even firing

Many older V6 engines were based on V8 engine designs, in which a pair of cylinders was cut off the front of V8 without altering the V angle or using a more sophisticated crankshaft to even out the firing interval. Most V8 engines share a common crankpin between opposite cylinders in each bank, and a 90° V8 crankshaft has just four pins shared by eight cylinders, with two pistons per crankpin, allowing a cylinder to fire every 90° to achieve smooth operation.

Early 90° V6 engines derived from V8 engines had three shared crankpins arranged at 120° from each other, similar to an inline 3-cylinder. Since the cylinder banks were arranged at 90° to each other, this resulted in a firing pattern with groups of two cylinders separated by 90° of rotation, and groups separated by 150° of rotation, causing a notorious *odd-firing* behavior, with cylinders firing at alternating 90° and 150° intervals. The uneven firing intervals resulting in rough-running engines with unpleasant harmonic vibrations at certain engine speeds.

An example is the Buick 231 odd-fire, which has a firing order 1-6-5-4-3-2. As the crankshaft is rotated through the 720° required for all cylinders to fire, the following events occur on 30° boundaries:

Angle	0°	90°	180°	270°	360°	450°	540°	630°
Odd firing	1	6	5		4	3		2
Even firing	1	4	5		6	3	2	

More modern 90° V6 engines avoid this problem by using split crankpins, with adjacent crankpins offset by 15° in opposite directions to achieve an even 120° ignition pattern. Such a 'split' crankpin is weaker than a straight one, but modern metallurgical techniques can produce a crankshaft that is adequately strong.

In 1977, Buick introduced the new "split-pin crankshaft" in the 231. Using a crankpin that is 'split' and offset by 30° of rotation resulted in smooth, even firing every 120°. However, in 1978 Chevrolet introduced a 90° 200/229 V6, which had a compromise 'semi-even firing' design using a crankpin that was offset by only 18°. This resulted in cylinders firing at 108° and 132°, which had the advantage of reducing vibrations to a more acceptable level and did not require strengthening the crankshaft. In 1985, Chevrolet's 4.3 (later the Vortec 4300) changed it to a true even-firing V6 with a 30° offset, requiring larger crank journals to make them adequately strong.

In 1986, the similarly-designed 90° PRV engine adopted the same 30° crankshaft offset design to even out its firing. In 1988, Buick introduced a V6 engine that not only had split crankpins, but had a counter-rotating balancing shaft between the cylinder banks to

eliminate almost all primary and secondary vibrations, resulting in a very smooth-running engine.

Racing use

Mercedes-Benz V6 DTM engine

The V6 engine was introduced into racing by Lancia in the early '50s. After good results with privately entered Aurelia saloons Lancia set a works competition department in 1951. Four B20 Coupes were entered in the '51 Mille Miglia and the one driven by Giovanni Bracco and Umberto Maglioli caused quite a stir by finishing second overally after the 4.1-litre Ferrari driven by Villoresi and Cassani, a car which had three times more power than the Lancia. After that encouraging start Lancia decided to carry on with the endurance racing program, first with specially prepared Aurelias (called *Da Corsa*) and then with specially built prototypes. A D24 with a 3,102 cc (189 cu in) V6 making 230 PS (170 kW) won the 1953 Carrera Panamericana with Juan Manuel Fangio at the wheel.

After that came the Ferrari Dino V6. Alfredo Ferrari (nicknamed Dino), son of Enzo Ferrari, suggested to him the development of a 1.5 L DOHC V6 engine for Formula Two at the end of 1955. The Dino V6 underwent several evolutions, including an increased engine displacement to 2,417 cc (147 cu in), for use in the Ferrari 246 Formula One car in 1958.

The use of a wide 120° bank angle is appealing for racing engine designers as it permits a low center of gravity. This design is even considered superior to the flat-6 in that it leaves more space under the engine for exhaust pipes; thus the crankshaft can be placed lower in the car. The Ferrari 156 built for new Formula One 1.5 L regulations used a Dino V6 engine with this configuration.

The Dino V6 engine saw a new evolution in 1966 when it was adapted to road use and produced by a Ferrari-Fiat joint-venture for the Fiat Dino and Dino 206 GT (this car was made by Ferrari but sold under the brand Dino). This new version was redesigned by Aurelio Lampredi initially as a 65° 2.0 L (~122 cu in) V6 with an aluminum block but was replaced in 1969 by a 2.4 L (~146 cu in) cast-iron block version (the Dino car was renamed the 246GT).

The Fiat Dino and Dino 246GT were phased out in 1974, but 500 engines among the last built were delivered to Lancia, who was like Ferrari already under the control of Fiat. Lancia used them for the Lancia Stratos which would become one of the most successful rally cars of the decade.

Alfa Romeo V6

The Alfa Romeo V6 was designed in the 1970s by Giuseppe Busso, the first car to use them being the Alfa Romeo 6. The over-square V6, with aluminium alloy block and

heads, has seen continuous use in road vehicles, from the Alfetta GTV6 onwards. A notable use of the *Bussone Sei* (Busso's big Six) V6 was the Alfa Romeo 155 V6 TI. Turbocharged, it had a peak power of 490 PS (360 kW; 480 hp) at 11,900 rpm. The 164 introduced a 3.0 L (~183 cu in) V6, a 2.0 V6 turbocharged in 1991 and in 1992, a 3.0 L DOHC 24 valve version. The Alfa 156 introduced a 2.5 L DOHC 24 valve version in 1997. The engine capacity was later increased to 3.2 L (~195 cu in), where it found application in the 156 GTA, 147 GTA, 166, GT, GTV and Spider 916. Production was discontinued in 2005.

Another influential V6 design was the Renault-Gordini CH1 V6, designed by François Castaing and Jean-Pierre Boudy, and introduced in 1973 in the Alpine-Renault A440. The CH1 was a 90° cast iron block V6, similar to the mass produced PRV engine in those two respects but otherwise dissimilar. It has been suggested that marketing purposes made the Renault-Gordini V6 adopt those characteristics of the PRV in the hope of associating the two in the public's mind.

Despite such considerations, this engine won the European 2 L prototype championship in 1974 and several European Formula Two titles. This engine was further developed in a turbocharged 2 L version that competed in Sports car and finally won the 24 Hours of Le Mans in 1978 with a Renault-Alpine A 442 chassis.

The capacity of this engine was reduced to 1.5 L to power the Formula One Renault RS01. Despite frequent breakdowns that resulted in the nickname of the 'Little Yellow Teapot', the 1.5 L finally saw good results in 1979.

Ferrari followed Renault in the turbo revolution by introducing a turbocharged derivative of the Dino design (a 1.5 L 120° V6) with the Ferrari 126. However, the 120° design was not considered optimum for the wing cars of the era and later engines used V angles of 90° or less.

Both Renault and Ferrari failed in their attempt to win the Drivers' Championship with V6 Turbo engines. The first turbocharged engine to win the championship was the Straight-4 BMW.

They were followed by a new generation of Formula One engines, the most successful of these being the TAG V6 (designed by Porsche) and the Honda V6. This new generation of engines were characterized by odd V angles (around 80°). The choice of these angles was mainly driven by aerodynamic consideration. Despite their unbalanced designs these engines were both quickly reliable and competitive; this is generally viewed as a consequence of the quick progress of CAD techniques in that era.

In 1989 Shelby tried to bring back the Can-Am series, using the Chrysler 3.3 L (201 in^3) V6 (not yet offered to the general public) as the powerplant in a special racing configuration making 255 hp (190 kW). This was the same year that the Viper concept was showed to the public.

Originally the plan was to produce two versions of this race car, a 255 hp (190 kW) version and a 500 hp (370 kW) model, the 255 hp (190 kW) version being the entry circuit. The cars were designed to be a cheap way for more people to enter auto racing. Since all the cars were identical, the winners were to be the people with the best talent, not the team with the biggest pockets. The engines had Shelby seals on them and could only be repaired by Shelby's shop, ensuring that all the engines are mechanically identical.

Only 100 of these 3.3s were ever built. Of these 100, 76 were put into Shelby Can-Am cars (the only 76 that were ever sold). No significant amount of spare parts were produced, and the unsold engines were used for parts/spares. The Shelby specific parts, such as the upper intake manifold, were never made available to the general public. According to a small article in the USA Today (in 1989), these cars were making 250 hp (190 kW) (stock versions introduced in 1990 produced 150 hp) and hitting 160 mph (260 km/h) on the track. The engine itself was not that far from a standard-production 3.3. The Shelby engine is only making about 50 hp (37 kW) more than the newest 3.3 factory engines from Chrysler. The Can-Am engine has a special Shelby Dodge upper intake manifold, a special Shelby Dodge throttle body, and a special version of the Mopar 3.3 PCM (which had this engine redlining at 6800 rpm).

Nissan also has a quite successful history of using V6's for racing in both IMSA and the JGTC. Development of their V6s for sports cars began in the early 1980s with the VG engine initially used in the Z31 300ZX. The engine began life as a SOHC, turbocharged 3.0L power plant with electronic fuel injection, delivering 230 PS (169 kW). The VG30ET was later revised into the VG30DETT for the Z32 300ZX in 1989. The VG30DETT sported both an additional turbocharger and an extra pair of camshafts, making the engine a genuine DOHC twin-turbo V6 producing 300 PS (221 kW). Nissan used both of these engines in its IMSA racing program through out the 1980s and 1990s each producing well over 800 hp (600 kW). In the Japan Grand Touring Car Championship, or JGTC, Nissan opted for a turbocharged version of its VQ30 making upwards of 500 hp (370 kW) to compete in the GT500 class.

Motorcycle use

Laverda showed a 996 cc V6 engined motorcycle at the 1977 Milan show. The motorcycle was raced in the 1978 Bol d'Or.

Marine use

Yamaha OX66 engine, as used in their outboard motor range

Chapter 9

Straight-Six Engine

A BMW M20B25 engine with the cylinder head removed, showing the pistons in the six cylinders of the engine

The **straight-six engine** or **inline-six engine** (often abbreviated **I6**, **L6** or **R6**) is a six cylinder internal combustion engine with all six cylinders mounted in a straight line along the crankcase. The single bank of cylinders may be oriented in either a vertical or an inclined plane with all the pistons driving a common crankshaft; in vehicles where this engine is installed inclined versus vertical, it is sometimes called a **slant-six engine**. The

straight-six layout is the simplest engine layout that possesses both primary and secondary mechanical engine balance, resulting in relatively low manufacturing cost combined with much less vibration than engines with fewer cylinders.

Displacement range

Usually, the straight-six design is used for engine displacements ranging from approximately 2 to 5 litres (120 to 310 cu in) in automobiles. It is also sometimes used for smaller engines but these, although very smooth running, tend to be rather expensive to manufacture in terms of power-to-cost ratio. Since the length of an engine is roughly proportionate to the number of cylinders in one bank (plus the width of one connecting rod in a "V" engine), they are inevitably physically longer than alternative layouts such as L4, V6, or V8.

The smallest production straight-six was found in the Benelli 750 Sei motorcycle, displacing 747.7 cc (45.63 cu in) (0.7477 L). Honda and Mike Hailwood raced in the 1960s with the RC166 250 cc (15 cu in) (0.25 L) six cylinder, 24-valve motorcycle engine. Though pre-World War II engines could be quite large by modern standards — such as the Rolls Royce Silver Ghost's 7.4 L engine and the 824 cuin (13.5 L) of the 1910s Peerless, Pierce, and Fageol, the largest modern passenger-car straight-sixes are the 4.2 L powerplants found in several Jaguars and AMCs, the 4.3 L Hemi Six, the 4.0 TVR Speed Six, the 4.0 Ford Barra, the 4.1 Chevrolet 250, the 4.2 Chevrolet Vortec 4200, 4.9 Ford, 4.8 Chevrolet, and the 5.0L of Hudson H-145 (produced until 1957). As of 2009, the Cummins B Series engine used in Dodge Ram pickup trucks displaced up to 6.7 L

The Gipsy Six and Gipsy Queen, made by the de Havilland Engine Company from 1935 until 1950, were inverted straight-six engines displacing 560.6 cubic inches (9.187 L). They were used in a variety of aircraft including the de Havilland Dragon Rapide and the Cierva W.9 experimental helicopter.

Because it is a fully balanced configuration, the straight-six can be scaled up to very large sizes for heavy truck, industrial and marine use, such as the 16 L (980 cu in) Volvo diesel engine and the 15 L Cummins ISX used in heavy vehicles. The largest are used to power ships, and use fuel oil. The straight-six can also be viewed as a scalable modular component of larger motors which stack several straight-sixes together, e.g. flat- or V-12s, W-18s etc.

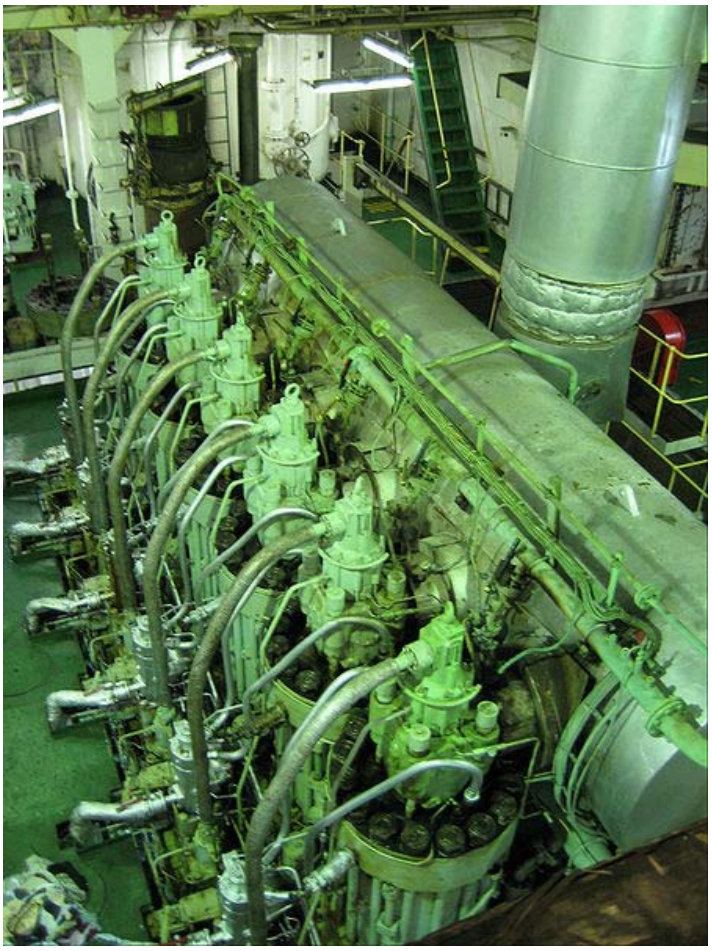
Modern trends

Historically, straight-six engines were introduced much earlier than V6 engines. While the first straight-six was manufactured in 1903 by Spyker, it was 1950 before a production V6 was introduced. V6s (unlike crossplane V8 engines) had intrinsic vibration problems that were difficult to eliminate without modern computer aided design techniques. The length of the straight-six was not a major concern in the older front-engine/rear-wheel drive vehicles, but the modern move to the more space-efficient front-

engine/front-wheel drive and transverse engine (left-to-right versus front-to-back) configurations in smaller cars made the length of the V6 (one half the length of an L6 with the same bore size, plus the width of one rod) a major advantage. As a result, in recent decades automobile manufacturers have replaced most of their straight-six engines (and many of their V8s) with V6 engines; Mercedes-Benz now uses V6 engines despite most of their lineup retaining the front-engine/rear-wheel layout.

Exceptions to the shift to V6 engines include BMW, which specializes in high-performance straight-sixes used in a lineup of front-engine/rear-wheel drive vehicles, Volvo, which designed a compact straight-six engine/transmission package to fit transversely in its larger cars, and the Australian Ford Falcon, which still uses a straight-six configuration. Straight-sixes also continue to be commonly used in medium to large trucks, and sport utility vehicles, where engine length is less of a concern. In 2002, General Motors introduced the Vortec 4200 as part of the modular straight-four, straight-five and straight-six GM Atlas engine line.

Balance and smoothness



An MAN B&W 6S60MC inline six cylinder low-speed diesel engine. This example is used on a 70,000 t (deadweight) bulk carrier, and produces 9,014.8 kW (12,089.0 hp) at 90.3 rpm (1.5 Hz)(703,130 ftlbs torque).

An inline six engine is in perfect primary and secondary mechanical balance, which can be achieved without using a balance shaft. The engine is in primary balance because the front and rear trio of cylinders are mirror images, and the pistons move in pairs. That is, piston #1 balances #6, #2 balances #5, and #3 balances #4, largely eliminating the polar rocking motion that would otherwise result. Secondary imbalance is avoided because an inline six cylinder crankshaft has six crank throws arranged in three planes offset at 120°. The result is that differences in piston speed at any given point in rotation are effectively canceled.

An inline four cylinder or V6 engine without a balance shaft will experience secondary dynamic imbalance, resulting in engine vibration. As a general rule, the forces arising from any dynamic imbalance increase as the square of the engine speed — that is, if the speed doubles, vibration will increase by a factor of four. In contrast, inline six engines have no primary or secondary imbalances, and with carefully designed crankshaft vibration dampers to absorb torsional vibration, will run more smoothly at the same crankshaft speed (rpm). This characteristic has made the inline six popular in some European sports-luxury cars, where smooth high-speed performance and good fuel economy are desirable. As engine reciprocating forces increase with the cube of piston mass, inline six is a preferred configuration for large truck engines.

Crankshaft design

Crankshafts on six cylinder engines generally have either four or seven main bearings. Larger engines and diesels tend to use the latter because of high loadings and to avoid crankshaft flex. Because of the six cylinder engine's smooth characteristic, there is a tendency for a driver to load the engine at low engine speeds. This can produce crankshaft flex in four main bearing designs where the crank spans the distance of two cylinders between main bearings. This distance is longer than the distance between two adjacent main bearings on a V6 with four mains, because the V6 has cylinder bores on opposite banks which overlap significantly; the overlap may be as high as 100%, minus the width of one connecting rod (1.00" or so). In addition, modern high-compression engines subject the crankshaft to greater bending loads from higher peak gas pressures, requiring the crankthrows to have greater support from adjacent bearings, so it is now customary to design straight-sixes with seven main bearings.

Many of the more sporty high-performance engines use the four bearing design because of better torsional stiffness (e.g., BMW small straight 6's, Ford's Zephyr 6). The accumulated length of main bearing journals gives a relatively torsionally flexible crankshaft. The four main bearing design has only six crank throws and four main journals, so is much stiffer in the torsional domain. At high engine speeds, the lack of torsional stiffness can make the seven main bearing design susceptible to torsional flex and potential breakage. Note that a V12 engine can be made with the same number of crank throws as the seven main bearing straight-six, although each throw must be wide enough to accept the connecting rods of both opposing cylinders requiring either that each rod be far narrower, or that the crankshaft length be extended. Another factor affecting large straight-six engines is the front mounted timing chain which connects any

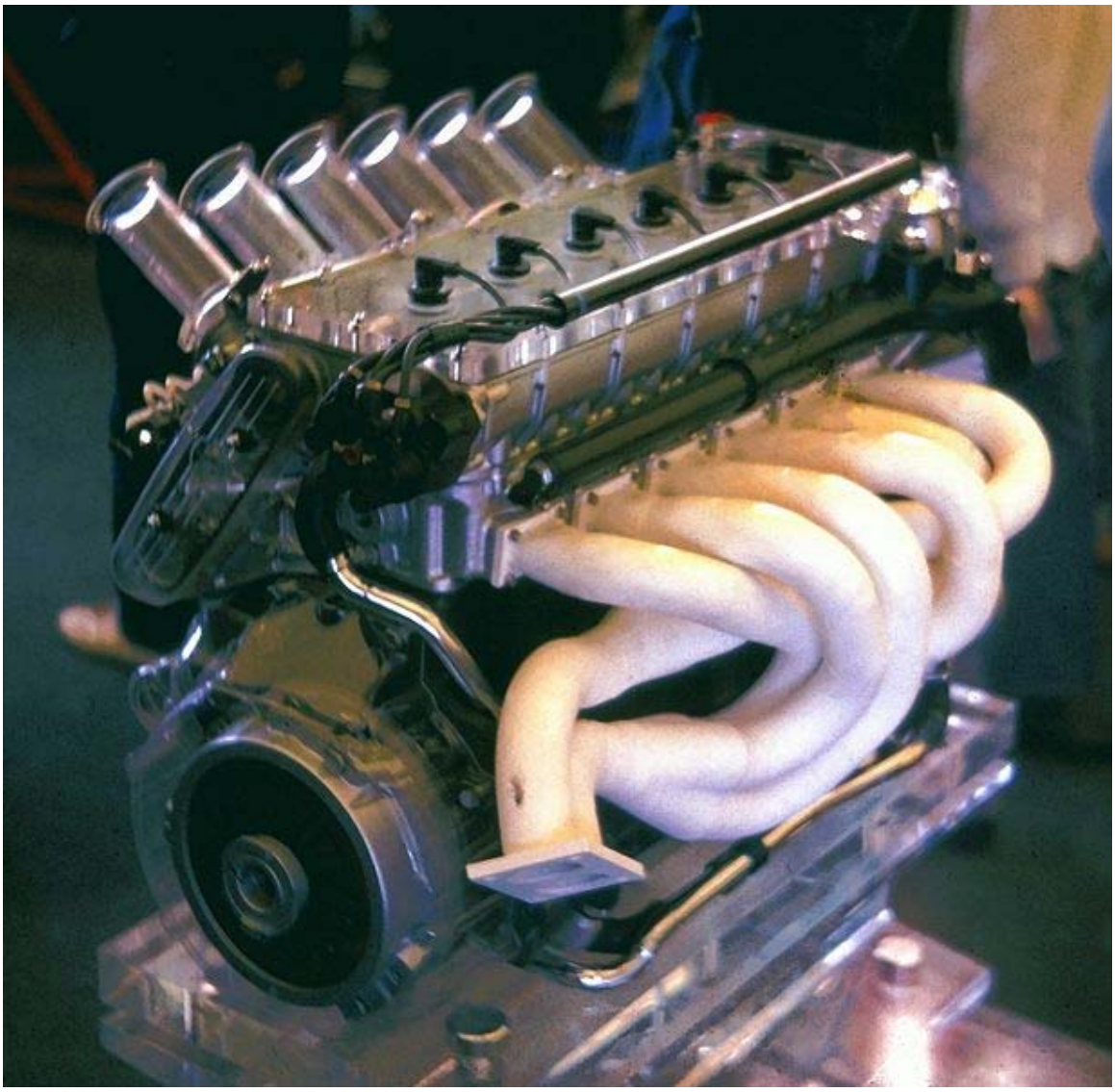
camshafts to the crankshaft. The camshafts are also quite long and subject to torsional flex as they in turn operate valves alternately near the front of the engine and near the rear. At high engine speeds, camshafts can flex torsionally in addition to the crankshaft, contributing to valve timing for the rear most cylinders becoming inaccurate and erratic, losing power, and in extreme cases resulting in mechanical interference between valve and piston — with catastrophic results. Some designers have experimented with installing the timing chain/gears in the middle of the engine (between cylinders 3 and 4) or adding a second timing chain at the rear of the engine. Either method can solve the problem at the cost of additional complexity.

Another factor affecting the ability of the large six cylinder engines to achieve high speed is the simple geometric reality of a relatively long stroke (undersquare) design. A straight-six is a long engine, and the designer is usually encouraged to make it as short as possible, while height is not usually a problem. Hence, the tendency to use a longer stroke and smaller bore than in a V engine to achieve a given capacity. By contrast, a long-stroke V engine tends to become too wide, which encourages increasing the bore rather than the stroke to increase displacement. The typically longer stroke of the straight-six increases crank throw and piston speed, and so tends to reduce the rpm rating of the engine.

History

The first inline six was produced by Spyker in 1903. By 1909, there were some eighty manufacturers using it, 62 in Britain alone, including Darracq, Delaunay-Bellville, Vertex, MMC, White and Poppe, Mutel, and Ford.

Continental Europe



BMW M1 engine

After becoming famous in the last year of World War I through their production of the liquid-cooled BMW IIIa aviation engine of straight-six layout, BMW introduced its first straight 6-cylinder automotive engine in 1933. It developed straight-six engines for the post-World War II era by adding two cylinders to its M10 four-cylinder design. In 1968, it introduced a M30 straight-six design with the same 30° slant, overhead camshaft layout, and 100 mm bore spacing as the four. It originally intended to follow up with a V8 engine line in the early 1970s, but when the 1973 oil crisis hit, BMW canceled its V8 plans and concentrated on refining and enlarging its straight-six lineup. These included a smaller straight-six in 2.0 and 2.3 L (120 and 140 cu in) displacements (the BMW M20), versions of the larger BMW M30 up to 3.8 L (230 cu in) (the S38B38); and beginning in 1983, a series of M21 straight-six diesel engines. In 1986, BMW introduced the M70 V12 which was essentially two 2.5 L (150 cu in) straight-sixes on the same crankshaft. In

the mid-90's, they produced a series of straight-6's based on the M50 architecture, the ultimate of which was the 330-360 hp S54, used up to 2008. BMW offered a straight-six for their following line up BMW 1 Series, BMW 3 Series, BMW 5 Series, BMW 6 Series, BMW 7 Series (Euro models), BMW X3, BMW X5, BMW X6, the retired Z3 and current BMW Z4.

Mercedes-Benz has used straight-six engines in its cars for around 100 years, starting in the first decade of the 20th century with a monstrous 10 L (610 cu in) engine producing 75 hp (56 kW), and producing in parallel through the World War I years the majority of German aviation engines of straight-six layout, culminating in the Mercedes D.III engine series of 1916-18 for the *Luftstreitkräfte*. Before and after the merger of Daimler and Benz in 1926, the combined company produced a variety of powerful straight-six engines, culminating in a 7 L (430 cu in) supercharged unit producing up to 300 hp (224 kW). Mercedes-Benz began the post-war era by producing straight-fours, but resumed making straight-sixes in 1951 with the M130, which were the beginning of the modern era of MB straight-sixes. Following that introduction, the company produced two lines of petrol (gasoline) straight-sixes at any one time, a small six and a larger six, in addition to its straight-fours, straight-fives, and later V8s and V12s. Although the company has used diesel engines in its cars since 1934, it introduced its first straight-six OM603 a 3.0 L (180 cu in) diesel in 1985. In 1996, the company replaced its petrol straight-sixes with a series of 90° M112 V6s, although it continued to produce diesel straight-sixes.

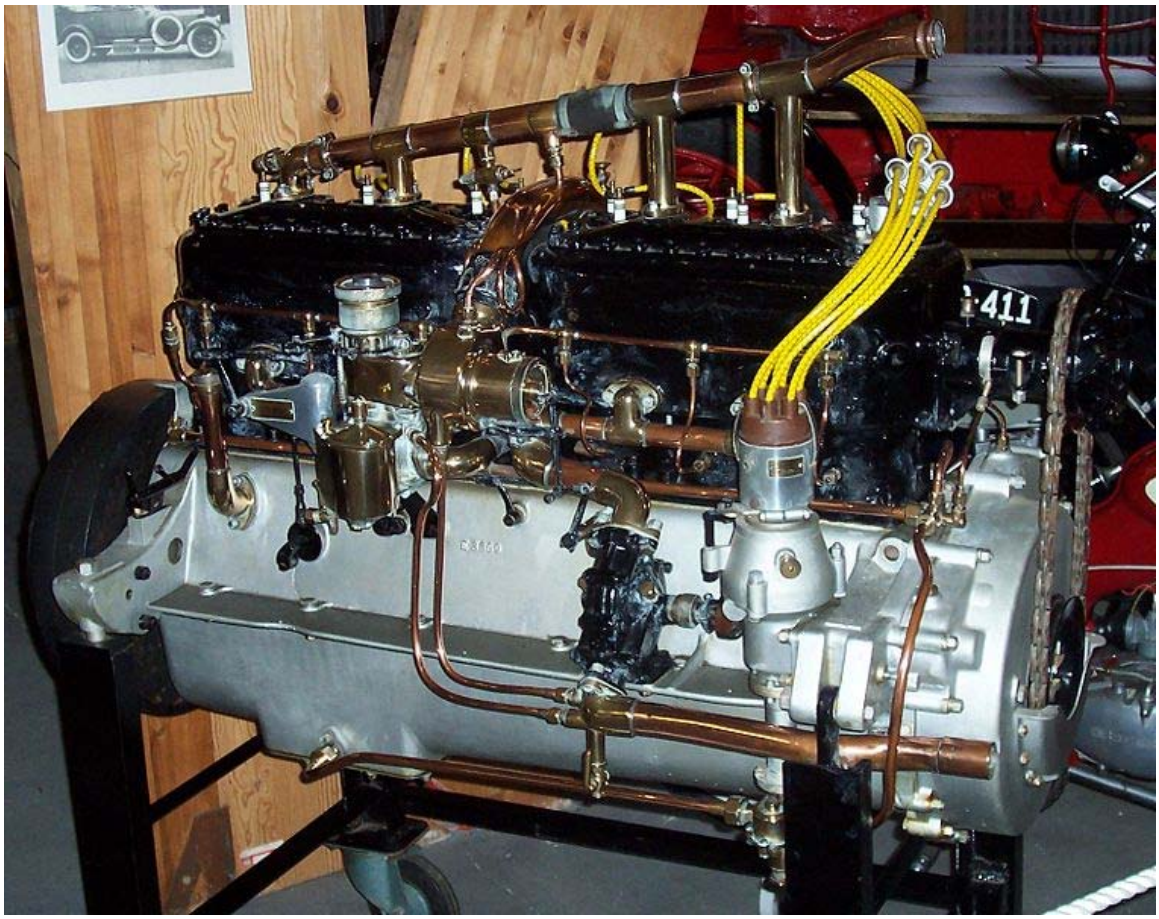
Volvo produced straight-sixes, the Volvo B30 engine (1969–1975), also the B6304 and the B6254 engines during late 1990s. As Volvo developed front-wheel drive models, they mounted their inline-six engine transversely by using a short transaxle package, and relocated engine-driven accessories. The 3.2 L (200 cu in) straight-six introduced in 2006 was only slightly longer than its straight-five, achieved by moving the camshaft drive to the back of the engine and sharing the same gear train with ancillaries mounted in otherwise unused space over top of the transmission. It was short for a straight-six and also very narrow. Volvo claims a transversely mounted inline engine leaves more crush space to protect against frontal impacts than a (shorter) transverse V6 or a longitudinally mounted inline-six.

Opel has also used a straight-six engine since 1930s until the early 1990s, ranging between 2.5 and 4.0 L (150 and 240 cu in). They powered Opel's top of the line models, including the Admiral, Kapitän, Monza, Senator, Omega, and Commodore.

In 1959, Saab had an experimental car with two transverse straight-three engines bolted together—the Saab Monster.

Alfa Romeo used straight-six engine in G1 and G2 models (1921–1923), RL model (1922–1927) and between 1925–1954 in Alfa Romeo 6C series road and racing cars, the 1500 version had one of the smallest straight-six engines (1,487 cc (90.7 cu in)). The last Alfa Romeo model using straight-six was Alfa Romeo 2600 (1961–1969).

United Kingdom



Rolls-Royce 40/50hp Silver Ghost 7,400cc side valve six cylinder engine

Jaguar XJ6 engine

The straight-six was the archetypal British engine for sports and luxury cars for many years. Rolls-Royce used straight-six engines until changes in their design made the shorter V8 engine layout more suitable. Jaguar and other manufacturers built straight-six engines from 1935 until the 1990s.

The most prominent of these was the Jaguar XK6 engine, which reportedly was developed during long nights during World War II when Jaguar founder William Lyons and his staff were on fire watch duty in the Jaguar factory in Coventry, and had nothing better to do than design a new engine. The result was displayed in the Jaguar XK120 at the London Motor Show in 1948. The 3.4 L (210 cu in) twin overhead camshaft XK6 engine engine was highly advanced compared to previous British engines. The Jaguar XK120 and the XK-powered Jaguar C-Type and Jaguar D-type, went on to score victories in races and rallies in the UK, Europe and North America. They dominated the 24 Hours of Le Mans during the 1950s, where Jaguar C-Types won in 1951 and 1953, and the D-Types had three more wins in 1955, 1956 and 1957. Subsequently, fitted to Lister Cars Lister-Jaguar, the D-type engine contributed to their success in international sportscar-racing in the late-1950s. The engine design, enlarged to 3.8 L (230 cu in), reached its apogee in the Jaguar E-type introduced in 1961, which was capable of 150 mph (240 km/h). In 1964, the XK engine was again enlarged to 4.2 L (260 cu in), which was considered the most powerful and refined of the series. The last XK-engined

Jaguar went out of production in 1986, but some XK engined cars such as the Daimler DS420 limousine were still available into 1990s. A variant of the 4.2 L engine powered some Scorpion light tanks. The XK6 engine was followed by the AJ6 and AJ16 engines. After Jaguar was acquired by Ford, these engines were replaced with the Ford Duratec-derived Jaguar AJ-V6 engine.

Aston Martin used a straight-six for many years, as did Austin-Healey in their Austin-Healey 3000. The latter used an engine originally built for the Austin Motor Company A105 saloon. Jensen also used Austin straight-six engines in their post WW-2 cars until 1962, re-engineering the Austin Sheerline's 4 L DS range to increase the power output. MG also used a straight-six in some pre-war cars (examples: MG K-type and MG N-type) and more recently in the MGC.

Bristol produced a straight-six until 1961, based on a BMW design, that was also used by many small automakers. Prior to World War II, Riley built a number of models fitted with straight-six engines, including the Kestrel 12/6 saloon and the MPH roadster.

The compact Triumph straight-six powered their high-end saloon and sports cars from the mid-1950s to the mid-1970s. It was available in 1.6 L (98 cu in), 2.0 L (120 cu in), and 2.5 L (150 cu in) capacities. Triumph claimed that their TR5 model was the first car in the UK to come with fuel injection as standard; the TR5 has a 2.5 L Triumph straight-six. Other Triumph vehicles that use the Triumph straight-six are:

- GT6 1966-73
- Vitesse 1962–71
- The 2000 Range 1963-77
- TR6 1969-76

The Austin 1800 range was expanded in 1972 when a 2.2 L six cylinder version of the BMC E-Series engine was installed transversely. The Austin and Morris models were called 2200 and the Wolseley version was called the Wolseley Six. Although this motor was originally designed by BMC in the sixties it was British Leyland who completed the planned upgrade to the 1800 range when they fitted this motor. This motor then went on to be used in the same configuration on the Leyland Princess which superseded the 1800 in 1975. This motor was designed to be as short as possible so the six cylinder would fit transversely, no water bores were between cylinders and the cylinders were too close together to allow boring; the only way to gain extra capacity was by lengthening the stroke.

The Rover SD1 saloon used a Triumph designed straight-six of 2.3 and 2.6 L (140 and 160 cu in) capacities as its base and mid-range engines.

British sports car company TVR designed its own straight-six, known as the Speed Six, which was also used in the Sagaris, with its capacity of 4 L (240 cu in). At 405 hp, it is the most powerful naturally-aspirated straight-6 ever fitted to a regular production car,

though some turbocharged engines are considerably more powerful (notably, the Toyota 2JZGTE and Nissan RB26DETT).

The Rover Company used straight-sixes in many of its saloon cars. A family of straight-4 and straight-6 engines with an unusual 'Inlet-Over-Exhaust' layout were developed. Introduced in the 1930s, these engines were used with great success in Rover's post war cars (the 'P3', 'P4' and 'P5' models). The sixes were available in a variety of capacities- 2.1 L (130 cu in), 2.2 L (130 cu in), 2.3 L (140 cu in), 2.6 L (160 cu in) and 3.0 L (180 cu in). In 1968, Rover began offering the 2.6 L engine as an option in long-wheelbase variants of its Land Rover 4x4. The engine remained available in the Land Rover until 1980, long after production of the other versions of the Rover IOE straight-six had stopped.

Ford UK produced a straight-six engine for the Zephyr and Zodiac range of passenger cars from the Mk1 of 1951 (2262 cc) through the Mk2 (2,553 cc (155.8 cu in)) and Mk3 until 1966. The straight-six was a four main bearing 12 overhead valve design with a short stroke. Rated output grew from just 65 hp (48 kW) in the Mk1 to 110 hp (82 kW) in the Mk3 Zodiac.

United States

1954 Hudson Wasp I6

Modified Chrysler slant-6

Carburated 1977 AMC 258 cu in (4.2 L)

The 5 millionth Jeep 4.0 L produced in Kenosha, Wisconsin on 2001-06-15

Engines of this type were popular before World War II in mid-range cars. Most manufacturers started building straight-six engines when cars grew too large for the inline-four engine.

After World War II, larger cars required larger engines, and buyers of larger cars tended to prefer V8s; performance sixes such as the Hudson Hornet 308 cu in (5.0 L) engine were exceptions to the rule, and were not often top sellers although it became one of the hottest cars on the road and dominated stock car racing (NASCAR) in the early Fifties.

After Chevrolet introduced its V8 in 1955, the straight-six became almost exclusively a base engine model pitched to economy-minded customers. Trucks (both light and heavy

duty) also incorporated the straight-six until the mid-1950s, and they are still used in light trucks available today. The new wave of compact cars that started in the late 1950s provided a suitable home for straight-six designs.

The Chrysler Slant-6 engines used in the Plymouth Valiant and Dodge Dart A-body models of the 1960s and 1970s featured a 30° inclined design to achieve a lower overall height. Originally designed to be built of aluminum, but after encountering problems in manufacturing the engines in aluminum, they were built in cast iron without changing the design to compensate for the stronger metal. Although it only had four crankshaft main bearings instead of the seven used by its competitors, they were the same size as those on the 426 cu in (7.0 L) Hemi V8. The Slant-6 achieved some success in racing when engineers utilized the slant of the engine for very long intake ports to boost horsepower by tuning the intake system. After 30 years of production, it was discontinued in favor of V6 engines because it was too long to mount transversely in front wheel drive cars.

Kaiser Jeep introduced the Tornado straight-6 for 1963. It was the first U.S. designed mass produced overhead cam (OHC) automobile engine. It was robust and built for heavy-duty performance, as well as featuring the lowest specific fuel consumption of all production gasoline engines in the market at the time. However, it was complex (by 1960s standards) for civilian vehicles in the U.S., but continued to be installed in military Jeeps and was also produced through 1982 by IKA in Argentina.

A "modern era" straight-six engine family was introduced by American Motors (AMC) in 1964. These lighter in weight engines were used in a variety of AMC passenger and Jeep utility vehicles. American Motors also sold their straight-sixes to International Harvester for powering International's "Light Line" of trucks: Scouts, pickups, and Travelalls. These engines were also assembled and marketed internationally. Some markets (such as Vehiculos Automotores Mexicanos [VAM] in Mexico) built their own specialized versions. This engine is considered to be one of the best ever made and it received modifications and upgrades as engine control technology improved. This engine was produced continuously for 42 years (even after Chrysler's buyout of AMC in 1987) all the way through 2006. It featured a durable design with a cast iron block and cylinder head, hydraulic lifters (with non-adjustable rockers), and seven main bearings. Since AMC cars were designed to take the weight of an optional V8, AMC was able to make their straight-sixes much stronger and heavier than they needed to be. As a result, the engine blocks were so sturdy that some were used in race cars in the Indianapolis 500. In the 1978 race, an AMC 199 cu in (3.3 L) engine built by Navarro produced 875 hp (652 kW) at 8500 rpm with 80 in (2,000 mm) of manifold pressure.

Ford and General Motors straight-sixes of the 1960s and 1970s were generally nondescript, except for the unusual (for the United States) OHC Pontiac six of the late-1960s. Although it was one of the few American straight-sixes of its era to be advertised as exceeding 200 hp (150 kW), it wooed few performance buyers away from V8s during the muscle car era, and was eventually discontinued in favor of a less costly but less powerful pushrod design.

American automakers found it more profitable to sell slow-speed straight-sixes as "economy" engines, and V8s as "performance" engines regardless of their horsepower potential, since big, unsophisticated, overhead valve engines were relatively cheap to manufacture, and fuel economy was not a concern prior to the 1973 oil crisis.

The trend after the fuel crises in the 1970s was towards smaller cars with better fuel economy. Despite this, straight-six engines became rare in American cars, although they continued to be used in trucks and vans. The decline of the straight-six was in response to the more compact size of the V6 layout. The straight-six required a longer engine compartment that was more appropriate to a larger car. The shorter V6 could be used in a shorter engine compartment and therefore fit better in a more compact car. It was also relatively easy to cut two cylinders off a V8 design to produce a V6 that could be manufactured on the same assembly line as the V8, which was convenient for American manufacturers.

Jeeps were an exception to the trend to V6s, and began offering AMC's 258 cu in (4.2 L), known as "High Torque," straight-sixes as a common engine option in 1972. These engines continued to receive upgrades that were advanced for their time, including the fuel-injected high-performance 4.0 L (240 cu in) version for the 1987 model year. The five millionth 4.0 L was produced in Kenosha, Wisconsin by Chrysler on 15 June 2001, autographed by the assembly workers, and donated to the Rambler Legacy Gallery. Usage of the AMC 4.0 declined in Jeep vehicles after the Jeep Cherokee (in North America) was replaced by the Liberty in 2002, which featured Chrysler's 3.7 L (230 cu in) V6 instead. It declined further after the 2005 introduction of the third generation Jeep Grand Cherokee, which also used the 3.7 L (230 cu in) V6. The last application of the 4.0 was in the 2006 Jeep Wrangler; for 2007, the engine was replaced with a 3.8 L (230 cu in) V6.

Ford used a straight-six in baseline Mustangs and in its other models for many decades. They were also found in F-series pickups, E-series vans, and Broncos (most notably the venerable Ford 300 inline six) until 1997 when they were replaced with a V6.

In 1989, Chrysler introduced the 5.9 L (360 cu in) Cummins B Series engine as an option on its pickup trucks. Displacing nearly 1 L per cylinder, this straight-six turbocharged diesel engine was an attractive alternative to the big gasoline V8s normally used on full-sized pickups, because of its better fuel economy and nearly twice as much low-speed torque. The usual marketing cachet of competing V8s from GM and Ford was offset by the "real" truck origin of the Cummins engine because earlier GM diesel V8s derived from gasoline engines had reliability problems.

In 2001, General Motors introduced a new family of straight engines, the *Atlas*, for use in the Chevrolet TrailBlazer/GMC Envoy. The straight-six was chosen for development because of the desirable operating characteristics of its self-balanced design.

Asia

Nissan S20 engine

Japanese automakers have used the straight-six since the 1960s in a wide range of vehicles. More recently though, Nissan (the 1984 300ZX switched to V6) and Toyota have changed to V6s, saying the straight-sixs were too long and expensive to manufacture for the engine compartments in their newer vehicles. The Nissan Skyline GT-R also used this layout and so had a long hood.

Toyota started with their F-series engine, and later the M, FZ, G, and JZ engines, and Nissan started with their H-series, and later the L (up until 1984) of the early Nissan Z-cars, also known as Fairlady Zs, as well as the RB series engines (in the R31-R34 Skyline). Honda built the Honda CBX1000 motorcycle from 1978-1981. In the 1990s, Toyota offered straight-sixes in all their lines: the G in the Altezza (and others); the M and its part-replacement, the JZ, in the Toyota Supra (and others); and the F and its replacement, the FZ, in the Land Cruiser. In the first decade of the 21st century, Toyota still offers the FZ-series, G-series, and the JZ-series engines.

Suzuki introduced the Verona a mid-sized front wheel drive car in 2004 with a straight-six and discontinued it 4 years later.

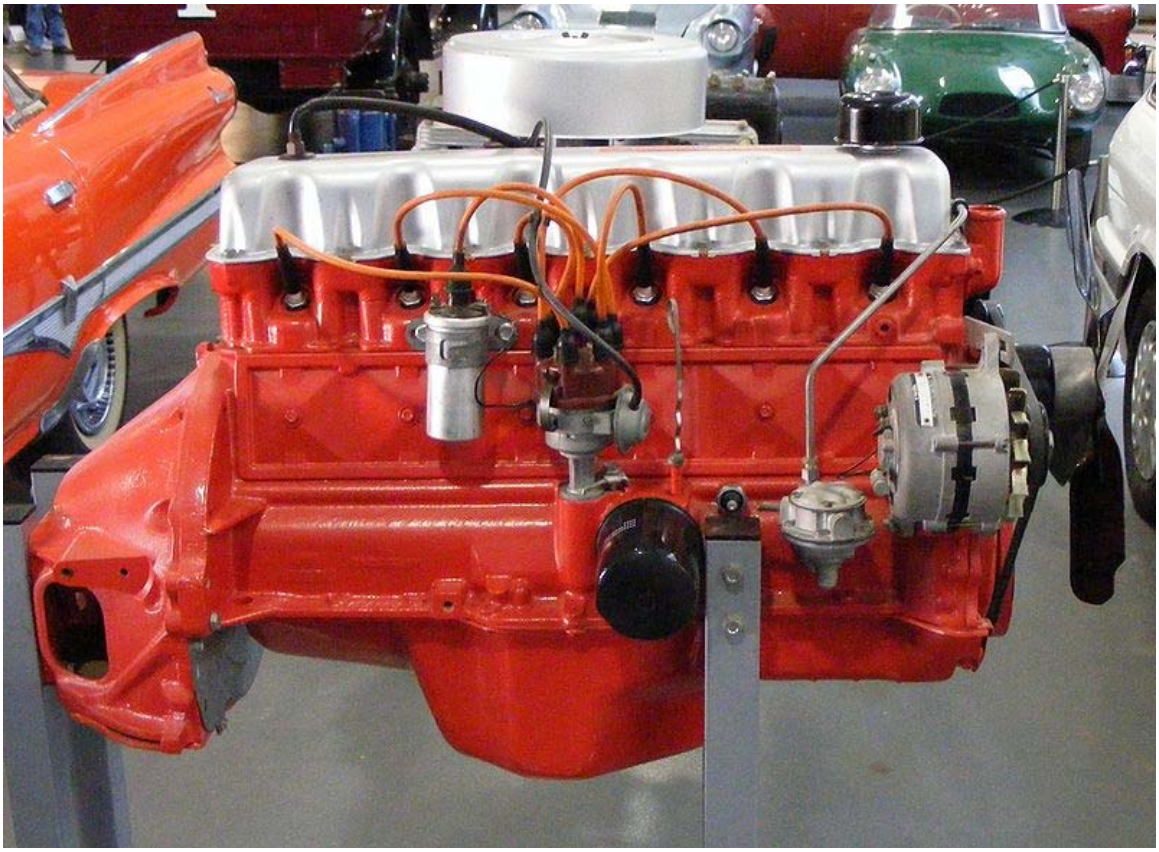
In Korea, GM Daewoo's FWD Magnus (sold abroad as the Chevrolet Evanda, Chevrolet Epica, Holden Epica or Suzuki Verona) comes with a Daewoo-designed straight-six. The

Daewoo engine is one of the few straight-sixes designed to be installed transversely in front-wheel drive cars, and it is an extremely short engine in its configuration.

Australia

Historically, all major manufacturers in Australia used straight-six engines.

BMC developed a straight-six engine based on the B-series engine in the late 1950s. It appeared in the Austin Freeway and Wolseley 24/80. Although successful in Australia, and tried successfully in the prototype MGC, the cost of retooling meant that the engine remained indigenous to Australia. In 1971, Leyland Australia replaced the Austin 1800 with the Austin X6 range, marketed as the Austin Tasman and Austin Kimberley . This car was based on the 1800's platform but had different front and rear styling and a new interior.It introduced a 2.2 L six cylinder version of the E-series engine four years ahead of the UK market. It has the distinction of being the first car with a transverse front-wheel-drive straight six. The car was supposed to offer more competition to the Australian big six market but it achieved less sales than the superseded four cylinder 1800. The E series six cylinder in 2.6 L form (achieved using a longer stroke) went on to be used in the Leyland P76 and the Marina.



Chrysler Hemi-6 Engine, unique to Chrysler Australia

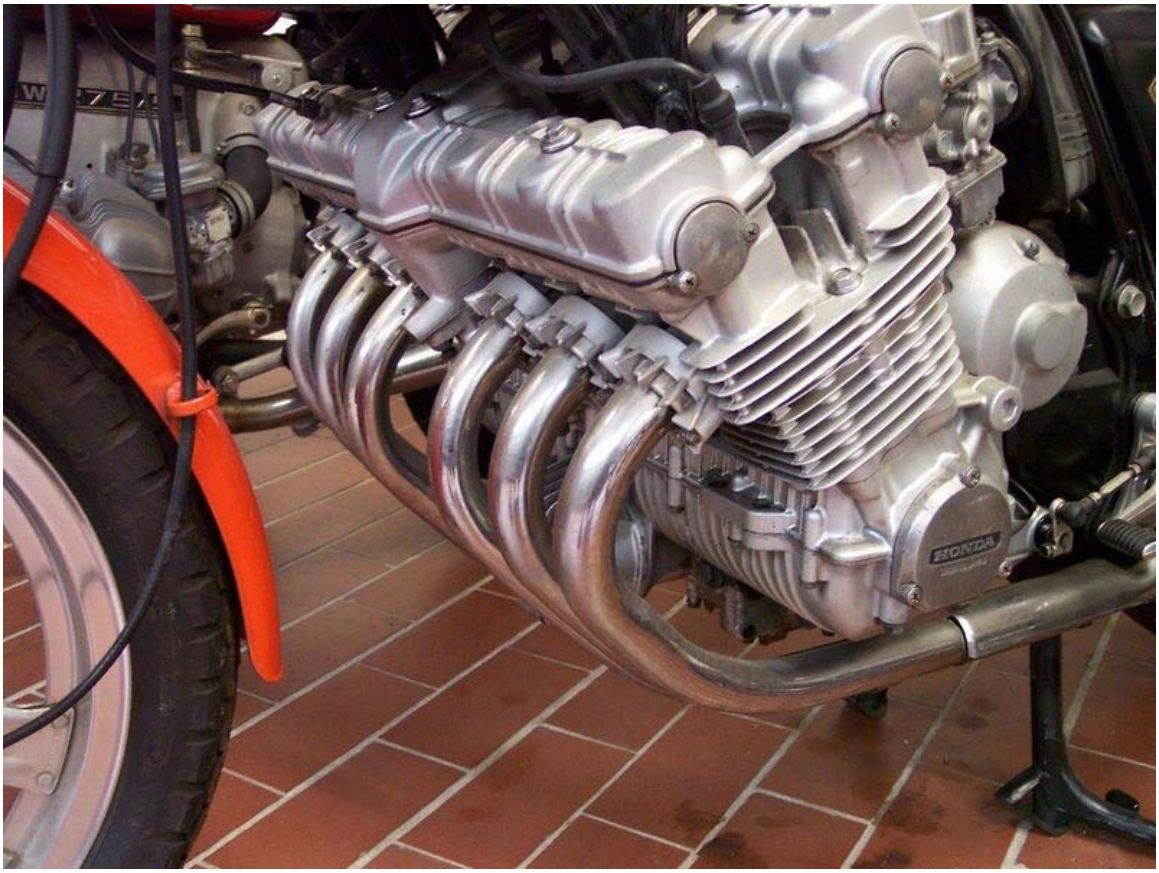
Chrysler had built the Slant 6 in Australia, and the unique to Australia Chrysler Hemi-6 Engine. These engines, made in 215 cu in (3.52 L), 245 cu in (4.01 L), and 265 cu in (4.34 L) capacity, were used in the Chrysler Valiant and the Valiant Charger producing up to 320 horsepower (239 kW). Chrysler no longer owns any factories in Australia.

Holden up until 1986 built their own straight-sixes, adapted from a Chevrolet design. A 132.5 cu in (2.171 L) unit (known as the *grey* motor) was used until 1963, with a minor increase in displacement in 1960 to 138 cu in (2.26 L) when it was replaced by a newer Chevrolet based design (known as the *red* engine) which was offered in different capacities. Holden engine sizes included the 138 cu in (2.26 L), 149 cu in (2.44 L), 179 cu in (2.93 L) (1964–1966), 161 cu in (2.64 L), 173 cu in (2.83 L) (1971–1984), 186 cu in (3.05 L) (1968–1971), and 202 cu in (3.31 L) (1971–1986, the largest and most popular of the series). This motor was firstly replaced by an imported RB20/30 Nissan straight-six, offered in 2.0 L (120 cu in) (in New Zealand) and 3.0 L (180 cu in) forms, until Holden's Buick designed 3.8 L (230 cu in) V6 replaced it outright in 1988. Holden now make and use the new global HFV6 in their local and export passenger cars.

Ford Australia has been producing straight-sixes since 1960, and is the only manufacturer in Australia to still build straight-sixes. Ford has built 144 cu in (2.36 L), 170 cu in (2.8 L), 188 cu in (3.08 L), 200 cu in (3.3 L), 221 cu in (3.62 L), 240 cu in (3.9 L), and 250 cu in (4.1 L) engines, with the 240 being called the 3.9 L (240 cu in), or 4.0 L (240 cu in) and the 200 being called the 3.3 L (200 cu in). They have been used since 1960 in the Falcon, 1972-1981 in the Cortina, and from 2004, in the Ford Territory. The current straight-six engines in the Falcon and Territory are called the Barra and have a 4.0 L (240 cu in) displacement.

The high-performance division of Ford Australia, Ford Performance Vehicles, produce vehicles equipped with the 4.0 L (240 cu in) 24-valve dual overhead camshaft (DOHC) turbocharged straight-six with variable cam timing, which produces 416 hp (310 kW) at 5,250 rpm (87.5 Hz) and 565 N·m (417 lb·ft) at 1,950 rpm (32.5 Hz) — the highest level of torque in any Australian production car to date.

Motorcycle use



Honda CBX1000 engine

Honda raced a number of straight-six engines in the Honda RC series of motorcycles, starting with the 249 cc (0.249 L) 3RC164 in 1964, with a bore of 39 mm, and a stroke of 34.8 mm. This became the RC165 in 1965. For 1966, bore and stroke became 41 mm and 31 mm in the RC166, continuing with the RC167 in 1967. Also in 1967, Honda raced the straight-six 297 cc (18.1 cu in) RC174 in the 350 class, with bore and stroke of 41 mm and 37.5 mm.

For road use, Honda introduced the Honda CBX1000 in 1978. Kawasaki introduced the 1,300 cc (79 cu in) KZ1300 in 1979. Benelli introduced the 750 Sei in 1976, which was later enlarged to 900 cc (55 cu in) to become the 900 Sei.

BMW has developed a straight six engine for motorcycle use, debuting in a concept bike in 2009, which will feature on the K1600GT and K1600GTL motorcycles in 2011. The 1,649 cc (100.6 cu in) engine is mounted transversely across the chassis.

Straight-six diesel engines

The straight-six in diesel engine form with a much larger displacement is commonly used for industrial applications. These include various types of heavy equipment, power generation, as well as transit buses or coaches. Virtually every medium-duty to large over-the-road truck employs an inline-six diesel engine. Its virtues are superior low-end torque, very long service life, smooth operation and dependability. On-highway vehicle operators look for straight-six diesels, which are smooth-operating and quiet. Likewise, off-highway applications such as tractors, marine engines, and electric generators need a motor that is rugged and powerful. In these applications, compactness is not as big a factor as in passenger cars, reliability and maintainability are much more important concerns.

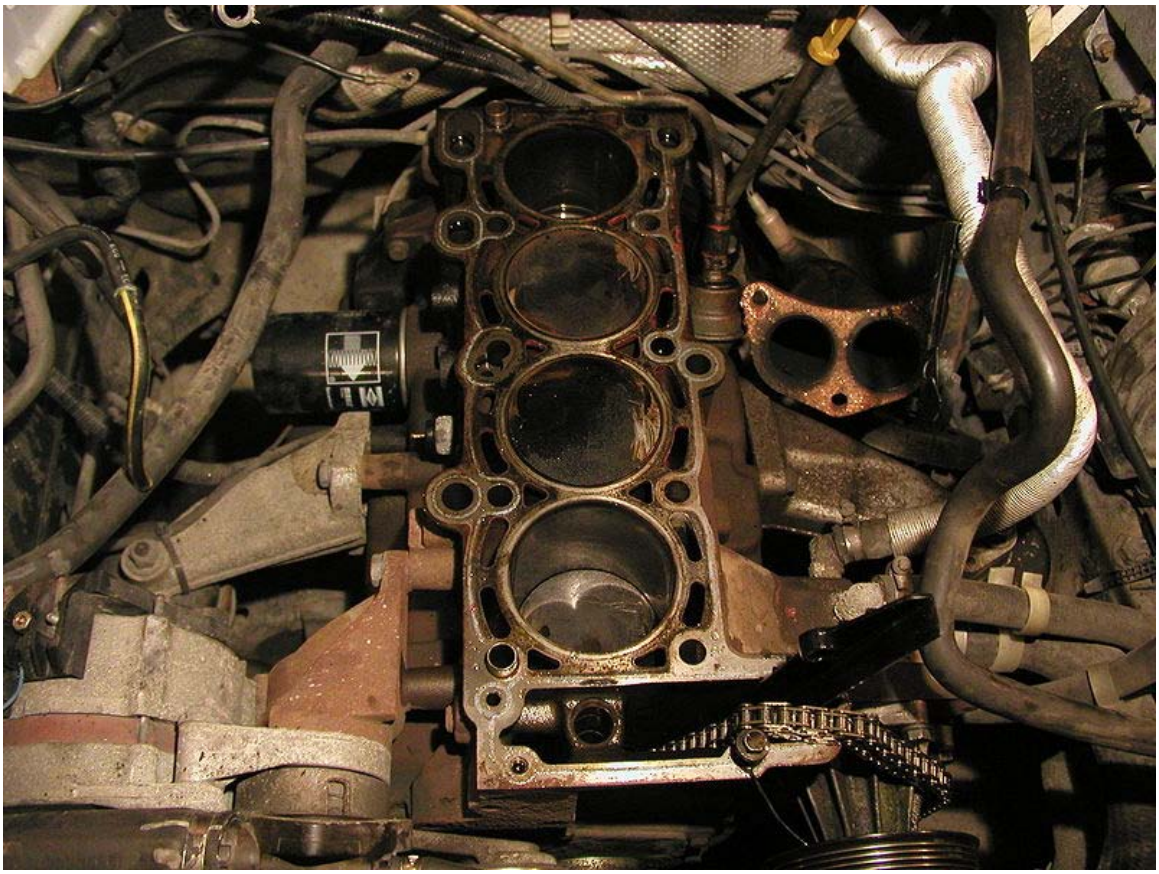
As with everyday passenger vehicles, the smooth running characteristics of the straight-six engine are what make it desirable for industrial use. The straight-six is a simple engine that is in both primary and secondary balance. This means it can be scaled up to very large sizes without causing excessive vibration. Most of the engine components and accessories can be located along both sides, rather than on top of or underneath the cylinder banks, means that access and maintenance is easier than on a V engine in a truck or industrial configuration. In addition, a straight-six engine is mechanically simpler than a V6 or V8 since it has only one cylinder head and in the overhead camshaft configuration has only half as many camshafts.

Notable versions include Toyota's normally-aspirated 2H and 12HT turbo from the 1980s, and the similar 1HZ 4 or 4.2 L. The 5.9 and 6.7 L straight-six Cummins found in the Dodge Ram and the DT series Navistar DT Engine of inline 6-cylinder medium-duty diesels by International Truck and Engine Corporation, are widely praised for use in the North American truck market. Caterpillar makes also engines in same displacement range for automotive, industrial and marine applications.

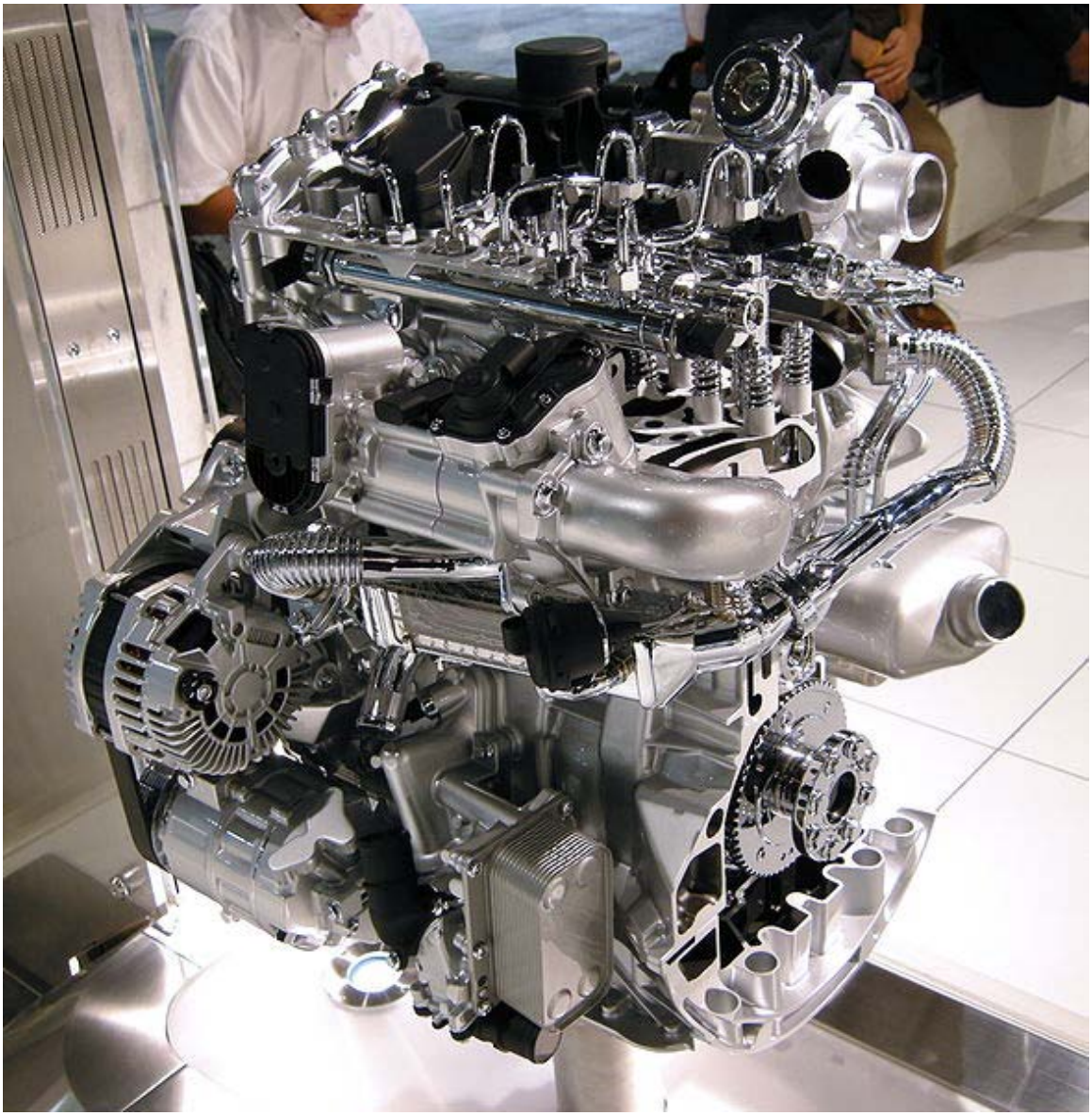
Diesel straight-sixes are also found in passenger cars, most notably those made by BMW. The twin-turbo M57 produces up to 272 bhp (203 kW; 276 PS) from its 3 L capacity, and it has won International Engine of the Year awards. Mercedes-Benz debuted the OM603 3.0 L (180 cu in) diesel in 1985. Nissan produced a range of straight-six diesels to be used in their vehicles. Some examples would be the Nissan RD engine, or the Nissan TD engine, which have similar characteristics to the RB engines. However, the RD engine was designed to be quiet, efficient and smooth, so it could be fitted to a range of Nissan luxury vehicles, such as the Nissan Laurel, and power output suffered as a result of these requirements.

Chapter 10

Inline-Four Engine



Ford inline-four engine with cylinder head removed



A cutaway photograph of Nissan M9R 2.0L Straight-4 DOHC Common rail Diesel Engine installed

The **inline-four engine** or **straight-four engine** is an internal combustion engine with all four cylinders mounted in a straight line, or plane along the crankcase. The single bank of cylinders may be oriented in either a vertical or an inclined plane with all the pistons driving a common crankshaft. Where it is inclined, it is sometimes called a **slant-four**. In a specification chart or when an abbreviation is used, an inline-four engine is listed either as **I4** or **L4** (for *longitudinal*, to avoid confusion between the digit 1 and the letter I).

The inline-four layout is in perfect primary balance and confers a degree of mechanical simplicity which makes it popular for economy cars. However, despite its simplicity, it suffers from a secondary imbalance which causes minor vibrations in smaller engines.

These vibrations become worse as engine size and power increase, so the more powerful engines used in larger cars generally are more complex designs with more than four cylinders.

The inline-four is the most common engine configuration in modern cars, while the V6 is the second most popular. Today most manufacturers of four cylinder engines for automobilles produce the inline-four layout, with Subaru's flat-four being a notable exception. In the late 2000s, with auto manufacturers making efforts to increase fuel efficiency and reduce emissions, due to the high price of oil and the economic recession, the proportion of new vehicles with four cylinder engines (largely of the inline-four type) has risen from 30 percent to 47 percent between 2005 and 2008, particularly in mid-size vehicles where a decreasing number of buyers have chosen the V6 performance option.

Displacement

This inline engine configuration is the most common in cars with a displacement up to 2.4 L. The usual "practical" limit of the displacement of inline-four engines in a car is around 2.7 L. However, Porsche used a 3.0 L four in its 944 S2 and 968 sports cars, and Rolls Royce produced several inline-four engines of 2,838 cc with basic cylinder dimensions of 3.5 in (89 mm) diameter and 4.5 in (110 mm) stroke (Rolls Royce B40);

Classic and Antique vehicles tended to have larger displacements to develop horsepower and torque. The Model A Ford was built with a 3.3 L inline-four engine.

Inline-four diesel engines, which are lower revving than gasoline engines, often exceed 3.0 L. Mitsubishi still employs a 3.2 L inline-four turbodiesel in its Pajero (called the Shogun or Montero in certain markets), and Tata Motors employs a 3.0 L inline-four diesel in its Spacio and Sumo Victa.

The Toyota B engine series of diesel engines varies in displacement from 3.0- 4.1 L. The largest engine in that series was used in the Mega Cruiser.

One of the strongest Powerboat-4-cylinders is the Volvo Penta D4-300 turbodiesel. This is a 3.7L-inline-4 with 300hp and 516ft-lbf(700Nm).

One of the strongest truck/tractor/railcar-4-cylinders is the MAN D0834 turbodiesel. This is a 4.6L-inline-4 with 220hp and 627ft-lbf(850Nm).

The Isuzu Forward is a medium-duty truck which is available with a 5.2 L inline-four engine that delivers 210hp and 470 ft-lbf (637Nm).

The Hino Ranger is a medium-duty truck which is available with a 5.1 L inline-four engine that delivers 175hp (129kW) and 465ft-lbf(631Nm). The earlier Hino Ranger even had a 5.3 L inline-four engine.

The Kubota M135X is a tractor with a 6.1 L inline-four. This turbo-diesel engine has a bore of 118 mm and a relative long stroke of 140 mm.

Larger inline-four engines are used in industrial applications, such as in small trucks and tractors, are often found with displacements up to about 4.6 L. Diesel engines for stationary, marine and locomotive use (which run at low speeds) are made in much larger sizes.

One of the largest inline-four engines is the MAN B&W 4K90 marine engine. This two stroke turbo-diesel has a giant displacement of 6,489 L. This results from a massive 0.9 meter bore and 2.5 meter stroke. The 4k90 engine develops 18,280 kW or 24,861 hp at 94 rpm and weighs 787 tons.

Displacement can also be very small, as found in kei cars sold in Japan, such as the Subaru EN series; engines that started out at 550 cc and are currently at 660 cc, with variable valve timing, DOHC and superchargers resulting in engines that produce 65 PS (48 kW; 64 bhp).

Balance and smoothness

Computer generated image showing the major internal moving parts of an inline-four engine with belt-driven double overhead camshafts and 4 valves per cylinder.

The inline-four engine is much smoother than one, two, and three cylinder engines, and this has resulted in it becoming the engine of choice for most economy cars, although it

can be found in some sports cars as well. However, the inline-four is not a fully balanced configuration.

An even-firing inline-four engine is in primary balance because the pistons are moving in pairs, and one pair of pistons is always moving up at the same time as the other pair is moving down. However, piston acceleration and deceleration are greater in the top half of the crankshaft rotation than in the bottom half, because the connecting rods are not infinitely long, resulting in a non sinusoidal motion. As a result, two pistons are always accelerating faster in one direction, while the other two are accelerating more slowly in the other direction, which leads to a secondary dynamic imbalance that causes an up-and-down vibration at twice crankshaft speed. This imbalance is tolerable in a small, low-displacement, low-power configuration, but the vibrations get worse with increasing size and power.

The reason for the piston's higher speed during the 180° rotation from mid-stroke through top-dead-centre, and back to mid-stroke, is that the minor contribution to the piston's up/down movement from the connecting rod's change of angle here has the same direction as the major contribution to the piston's up/down movement from the up/down movement of the crank pin. By contrast, during the 180° rotation from mid-stroke through bottom-dead-centre and back to mid-stroke, the minor contribution to the piston's up/down movement from the connecting rod's change of angle has the opposite direction of the major contribution to the piston's up/down movement from the up/down movement of the crank pin.

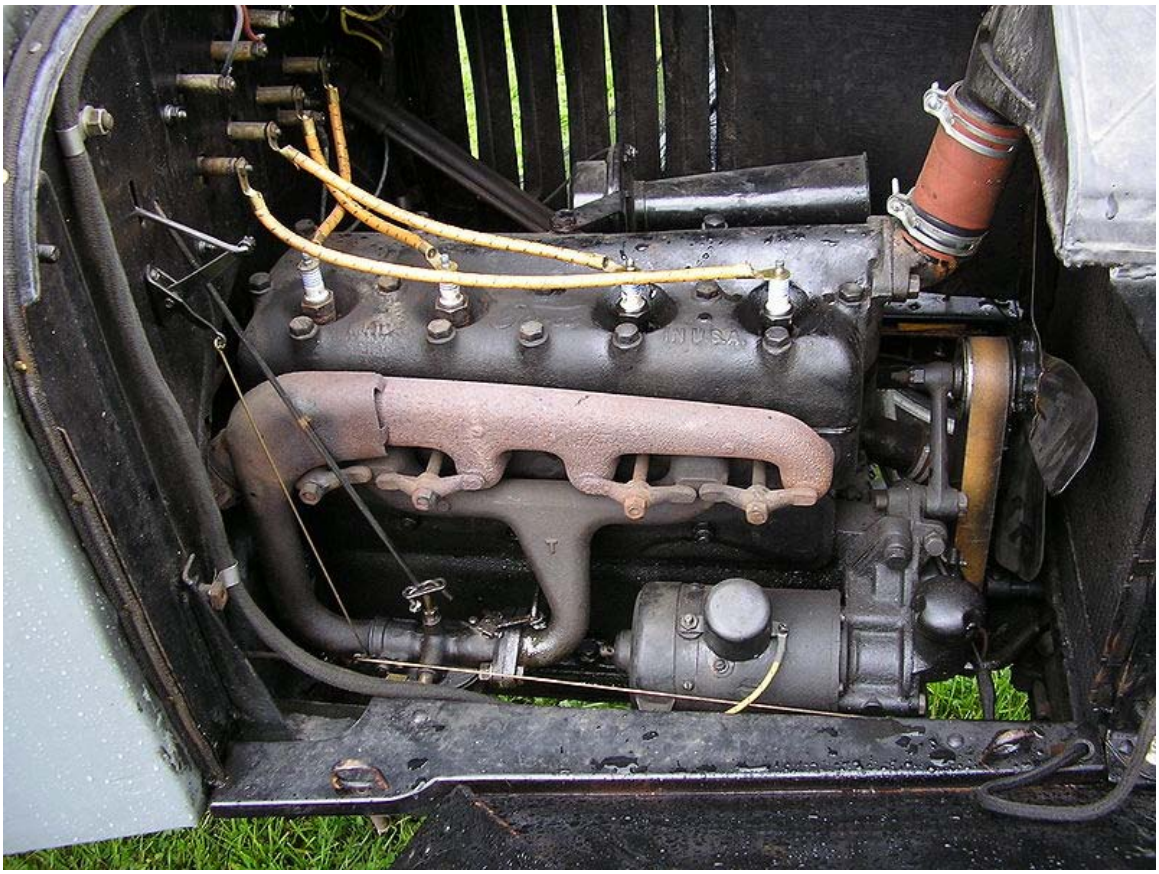
Most inline-four engines below 2.0 L in displacement rely on the damping effect of their engine mounts to reduce the vibrations to acceptable levels. Above 2.0 L, most modern inline-four engines now use balance shafts to eliminate the second-order harmonic vibrations. In a system invented by Dr. Frederick W. Lanchester in 1911, and popularised by Mitsubishi Motors in the 1970s, an inline-four engine uses two balance shafts, rotating in opposite directions at twice the crankshaft's speed, to offset the differences in piston speed. However, in the past, there were numerous examples of larger inline-fours without balance shafts, such as the Citroën DS 23 2,347 cc engine that was a derivative of the Traction Avant engine, the 1948 Austin 2,660 cc engine used in the Austin-Healey 100 and Austin Atlantic, the 3.3 L flathead engine used in the Ford Model A (1927), and the 2.5 L GM Iron Duke engine used in a number of American cars and trucks. Soviet/Russian GAZ Volga cars and UAZ SUVs, vans and light trucks used aluminium big-bore inline-four engines (2.5 or later 2.9 L) with no balance shafts from the 1950s-1990s. These engines were generally the result of a long incremental evolution process and their power was kept low compared to their capacity. However, the forces increase with the square of the engine speed — that is, doubling the speed makes the vibration four times worse — so modern high-speed inline-fours have more need to use balance shafts to offset the vibrations.

Four cylinder engines also have a smoothness problem in that the power strokes of the pistons do not overlap. With four cylinders and four strokes to complete in the four-stroke cycle, each piston must complete its power stroke and come to a complete stop

before the next piston can start a new power stroke, resulting in a pause between each power stroke and a pulsating delivery of power. In engines with more cylinders, the power strokes overlap, which gives them a smoother delivery of power and less vibration than a four can achieve. As a result, six- and eight- cylinder engines are generally used in more luxurious and expensive cars.

Automobile use

Notable production inline-four engines



Ford Model T engine

1970 Alfa Romeo 1750 GTV engine

The smallest automobile production inline-four engine powered the 1962-1970 Mazda P360 Carol kei car. Displacing just 358 cc, the Mazda *DA* was a conventional but tiny pushrod engine. Honda produced, from 1963–1967, a 356 cc (21.7 cu in) inline-four engine for the T360 truck. Inline-four motorcycle engines are built down to 250 cc, e.g. in the Honda CBR250.

Most inline-four engines, however, have been over 700 cc (43 cu in) displacement. A practical upper limit could be placed in the 2.5 L range for contemporary production cars. Larger engines (up to 6.1 L) have been seen in tractors (Kubota M135X) and medium duty truck use (Isuzu Forward, Hino Ranger), especially using diesel fuel (one of the strongest is the MAN D0834 engine with 220hp and 627ft-lbf(850Nm)). The use of balance shafts allowed Porsche to use a 3.0 L (2990 cc) inline-four engine on road cars first in the 944 S2, but the largest modern non-diesel was the plain 3,188 cc (194.5 cu in) *195* in the 1961 Pontiac Tempest.

Currently, one of the largest straight-4 engines in production is General Motors' Vortec 2900 installed in the GMC Canyon and Chevrolet Colorado small pickup trucks. It shares the same 95.5 mm bore and 102 mm (4.0 in) stroke as the larger inline-five Vortec 3700. The latest version of the Vortec 2900, the LLV, displaces 2.9 L (2921 cc, 178 in^3) and produces 185 hp (138 kW) at 5600 rpm and 195 ft·lbf (263 N·m) at 2800 rpm. Engine

redline is 6300 rpm. Another example of a large inline-four engine is the Russian 2.89 L UMZ 421 series UMZ engine.

In the early 20th century, bigger engines existed, both in road cars and sports cars. Due to the absence of displacement limit regulations, manufacturers took increasing liberties with engine size. In order to achieve power over 100 hp (75 kW), most engine builders simply increased displacement, which could sometimes achieve over 10.0 L. One of the biggest inline-fours of its time was De Dietrich 17,000 cc engine. Its cubic capacity is over twice the size of the Cadillac's 500 CID 8.2 L V8 engine, which was considered the largest engine of its type in the 1970s. These engines ran at very low rpm, often less than 1,500 rpm maximum, and had a specific output of about 10 hp/L. The US tractor industry both farm and industrial relied on large four cylinder power units until the early 1960s, when six cylinder designs came into favor. International Harvester built a large 5.7 litre (350 CID) four cylinder for their WD-9 series tractors.

Other technologically or historically notable engines using this configuration include:

- Alfa Romeo Twin Cam engine - one of the first mass produced twin cam engines produced from 1954. Also first engine in production car with variable valve timing.
- BMC A-Series engine - the first engine to be used in a transverse drive train powering the front wheels of a mass-produced automobile (Mini).
- Chevrolet Cosworth Twin-Cam Vega - 2.0 L all aluminum (block & head), DOHC, 16 valves, electronic fuel injection, stainless steel header.
- Dodge A853 - intercooled turbo engine from the SRT-4, set the land speed record for 4 cylinder production cars at the Bonneville Salt Flats.
- Ford Model T engine - one of the most-widely produced engines in the world.
- Ford Model A engine - the follow-up design to the Model T.
- GM Quad-4 engine - twin-cam Oldsmobile engine offered in GM small, sporty cars.
- Honda ED engine - first use of Honda's CVCC technology.
- Honda F20C engine - its 240 horsepower (180 kW) from 2.0 L was the highest specific output of its time, particularly noteworthy in that it achieved this without forced induction.
- Mitsubishi Sirius engine - includes the 4G63, which has the highest specific output of a turbocharged production engine in the world with the Lancer Evolution FQ-400 available in the United Kingdom (202.9 hp/L)
- GM Iron Duke engine - A versatile 151 CID 2.5 L 95 horsepower (71 kW) engine used in many GM cars in longitudinal configuration powering rear wheels or a transverse configuration powering front wheels or rear wheels. "Super Duty" racing versions of the Iron Duke were developed by Pontiac Racing.
- Triumph Slant-4 engine - the first mass-produced multi-valve engine for Triumph and an early turbo engine for Saab.
- Willys L-134 engine - nicknamed the Go Devil engine. Powered the World War II Jeep and post-war models. Notably undersquare, with 3.125 in (79.4 mm) bore and 4.375 in (111.1 mm) stroke.

In the late 2000s, with auto manufacturers making efforts to increase fuel efficiency and reduce emissions, due to the high price of oil and the economic recession, the proportion of new vehicles with inline-four engines have increased considerable at the expense of V6 and V8 engines. This is particularly evident in mid-size vehicles where a decreasing number of buyers have chosen the V6 performance options, and in fact the 2010 Hyundai Sonata no longer has a V6 option, instead offering a 2.0T (2.0L turbocharged and directly-injected) inline-four as the upgrade engine. The Volkswagen Group in particular has made widespread use of its 2.0 TFSI inline-four, which also features turbocharging and direct injection, as a performance option for its Volkswagen Golf (Golf GTI) and as the base engine for its Audi A4 (in the latter capacity where it provides superior torque to contemporaries with V6 engines, namely Audi's own 3.2 FSI V6). A tuned version of the Volkswagen 2.0 TFSI engine powers the Audi TTS

Racing use

1913 saw a Peugeot driven by Jules Goux winning the Indianapolis 500. This car was powered by an inline-four engine designed by Ernest Henry. This design was very influential for racing engines as it featured for the first time dual overhead camshafts (DOHC) and four valves per cylinder, a layout that would become the standard until today for racing inline-four engines.

This Peugeot was sold to the American driver "Wild Bob" Burman who broke the engine in 1915. As Peugeot couldn't deliver a new engine during World War I, Burman asked Harry Arminius Miller to build a new engine. With John Edward and Fred Offenhauser, Miller created a Peugeot-inspired inline-four engine. This was the first version of the engine that would dominate the Indianapolis 500 until 1976 under the brand Miller and later Offenhauser. The Offenhausers won five straight victories at Indianapolis from 1971 to 1976, and it was not until 1981 that they were eliminated as competitors by engines such as the Cosworth V8 engine.

Many cars produced for the pre-WWII voiturette Grand Prix motor racing category used inline-four engine designs. 1.5 L supercharged engines found their way into cars such as the Maserati 4CL and various English Racing Automobiles (ERA) models. These were resurrected after the war, and formed the foundation of what was later to become Formula One, although the straight-eight supercharged Alfettas would dominate the early years of F1.

Another engine that played an important role in racing history is the inline-four Ferrari engine designed by Aurelio Lampredi. This engine was originally designed as a 2 L Formula 2 engine for the Ferrari 500, but evolved to 2.5 L to compete in Formula One in the Ferrari 625. For sports car racing, capacity was increased up to 3.4 L for the Ferrari 860 Monza.

Yet another very successful engine was the Coventry Climax inline-four originally designed by Walter Hassan as a 1.5 L Formula 2 engine. Enlarged to 2.0 L for Formula

One in 1958, it evolved into the large 2495 cc FPF that won the Formula One championship in Cooper's chassis in 1959 and 1960.

Motorcycle use

Honda CB750 engine

For racing, Honda built inline-four engines as small as a 125 cc for the Honda 125/4. This engine was replaced by a 125 cc straight-five engine. The largest proprietary inline-four engine in a commercially-produced motorcycle is the 1402 cc engine in the Suzuki GSX1400.

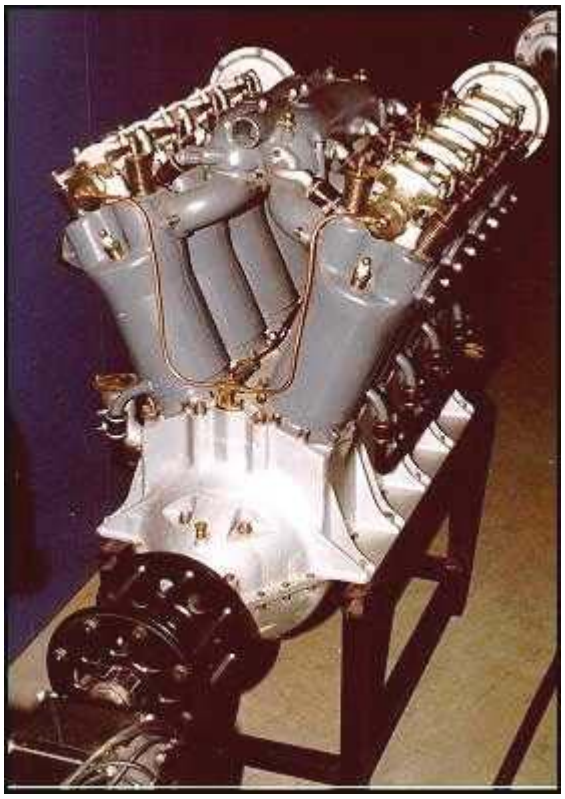
Modern inline-four motorcycle engines first gained their popularity with Honda's SOHC CB750 in the 1970s. Since then, the inline-four has become one of the most common engine configurations in street bikes. Outside of the cruiser category, the inline-four is simply the most common configuration because of its relatively high performance-to-cost ratio. All of the Japanese motorcycle manufacturers offer motorcycles with inline-four engines, as does MV Agusta and BMW who employ both longitudinal and transverse-mounted engines. Even the modern Triumph company has offered inline-four-powered motorcycles, though they were discontinued in favour of a triple.

The 2009 Yamaha R1 has an interesting inline-four engine that does not fire at even intervals of 180°. Instead, it uses a crossplane crankshaft that prevents the pistons from

simultaneously reaching top dead centre. This results in increased torque at lower engine speeds.

Chapter 11

V8 Engine



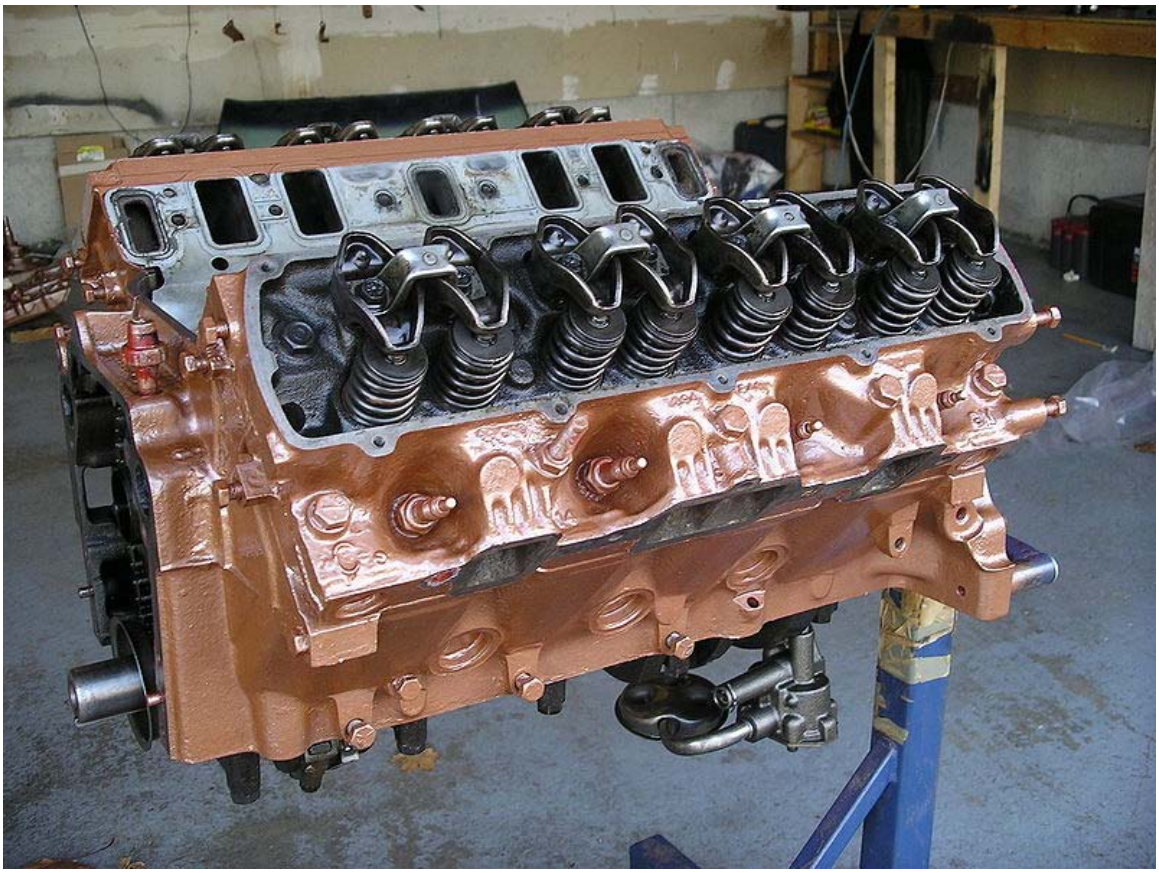
The Liberty V8 aircraft engine clearly shows the configuration, although modern automotive versions use a 90 degree block angle.

Bare block of an American Motors V8 engine showing the four cylinders on each side of the V configuration

A **V8 engine** is a V engine with eight cylinders mounted on the crankcase in two banks of four cylinders, in most cases set at a right angle to each other but sometimes at a narrower angle, with all eight pistons driving a common crankshaft.

In its simplest form, it is basically two straight-4 engines sharing a common crankshaft. However, this simple configuration, with a single-plane crankshaft, has the same secondary dynamic imbalance problems as two straight-4s, resulting in vibrations in large engine displacements. As a result, since the 1920s most V8s have used the somewhat more complex crossplane crankshaft with heavy counterweights to eliminate the vibrations. This results in an engine which is smoother than a V6, while being considerably less expensive than a V12 engine. Racing V8s continue to use the single plane crankshaft because it allows faster acceleration and more efficient exhaust system designs.

Applications



Assembled overhead valve engine with heads and complete valve train but without manifolds, rocker covers, timing chain cover or oil pan

Assembled and installed with all components as seen in a rear-wheel drive vehicle

The V8 with a crossplane crankshaft is a common configuration for large automobile engines. V8 engines are rarely less than 3.0 L (183 cu in) in displacement and in automobile use have exceeded 8.2 L (500 cu in) in production vehicles. Industrial and marine V8 engines can be much larger.

V8s are generally only standard on more powerful muscle cars, pony cars, sports cars, luxury cars, pickup trucks, and SUVs. However they are often options in vehicles which have a V6 or straight-6 as standard engine. In some cases, V6 engines were derived from V8 designs by removing two cylinders maintaining the V-angle so they can be built on the same assembly lines as the V8s and installed in the same engine compartments with few modifications. Some of these employed offset crankpins driving connecting rod pairs, enabling a regular firing sequence.

The traditional 90° big-bore V8 engine is generally too wide and too long to fit easily in vehicles with a transverse engine front-wheel drive layout, so its applications are limited to rear-wheel drive sports cars, muscle cars, pony cars, luxury cars and light trucks. The shorter and occasionally narrower V6 engine is easier to fit in small engine compartments, but a few compact V8 engines are used in transverse FWD and transverse AWD engine configurations in larger cars, such as Cadillacs and Volvos. These engines

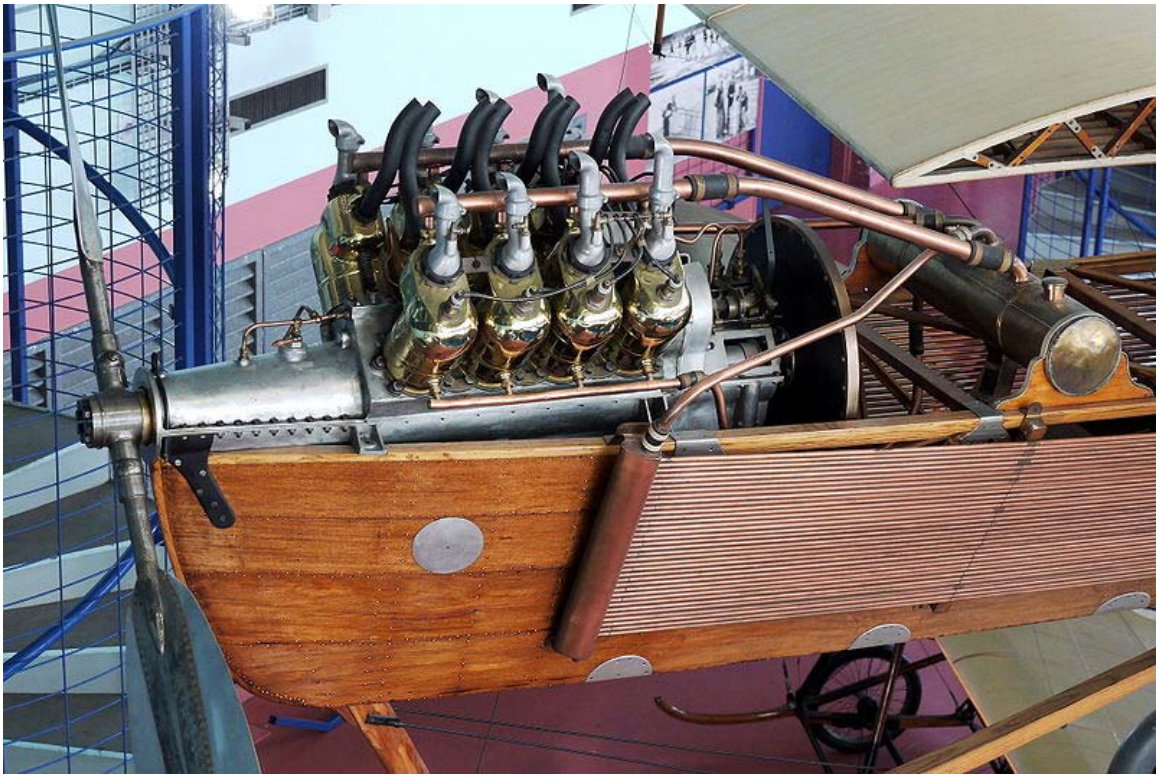
often have tighter cylinder bore spacings, narrower cylinder bank angles, and other modifications to reduce their space requirements.

V8s are common in purpose-designed engines for racing cars. They usually have flat-plane crankshafts, since a crossplane crankshaft results in uneven firing into the exhaust manifolds which interferes with engine tuning, and the crossplane's heavy crankshaft counterweights prevent the engine from accelerating rapidly. They are a common engine configuration in the highest echelons of motorsport, especially in the USA where it is required in IRL, ChampCar and NASCAR. V8 engines are also used in Australian motorsport, most notably in the V8 Supercars. Formula One began the 2006 season using naturally aspirated 2.4 L (~146 cu in) V8 engines, which replaced the 3.0 L (~183 cu in) V10 in a move to reduce costs and power.

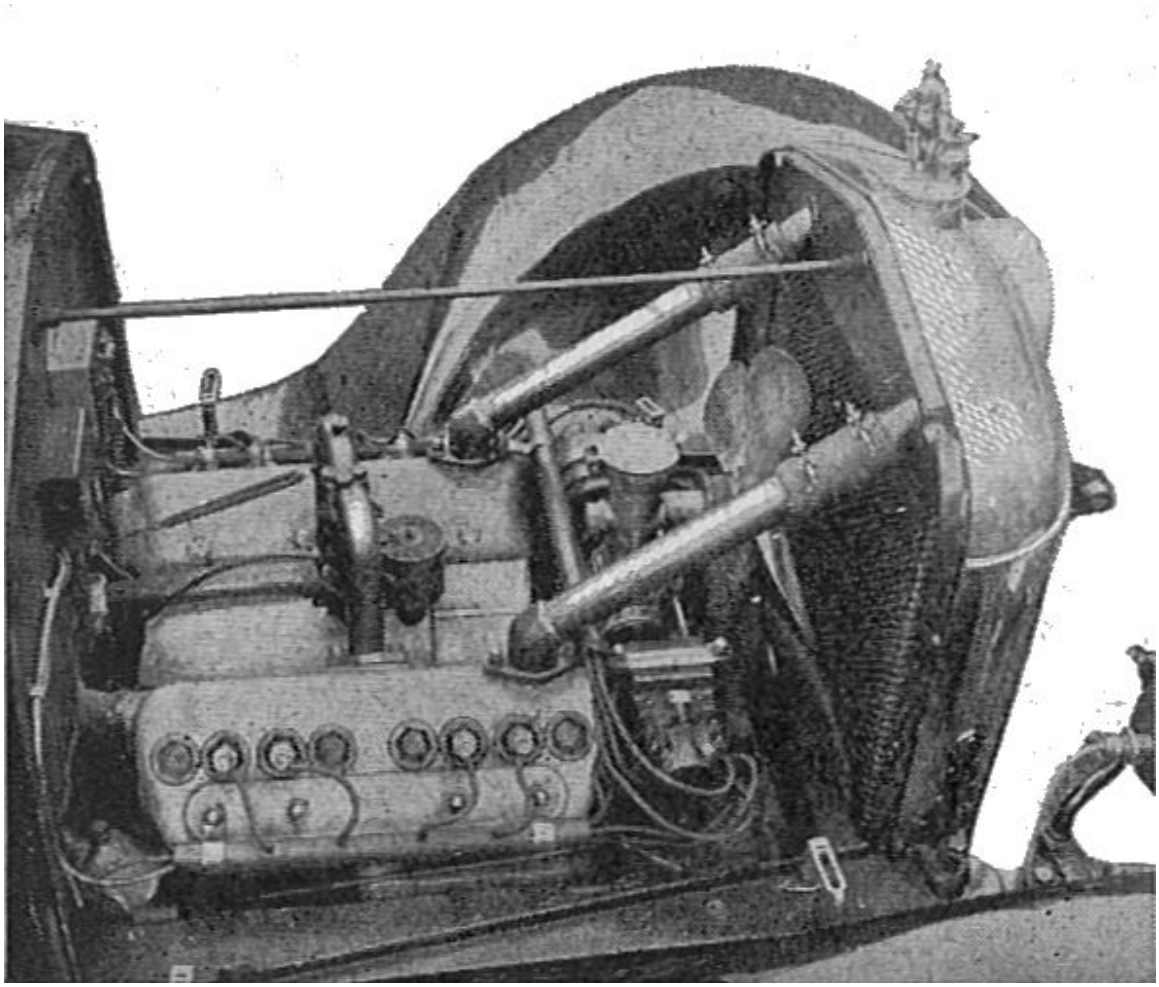
Heavy trucks and railroad locomotives tend to use the straight-6 configuration since it is simpler and easier to maintain, and because the straight-6 is an inherently balanced layout which can be scaled up to any size necessary. Large V8s are found in the larger truck and industrial equipment lines, however.

Although it was the early choice for aircraft engines, the V8 engine is seldomly used in modern aircraft engine as the typically heavy crankshaft counterweights are a liability. Modern light planes commonly use the flat-8 configuration instead as it is lighter and easier to air cool, in addition it can be manufactured in modular designs sharing components with flat-4 and flat-6 engines.

History



1909 Antoinette VII aircraft with Antoinette V8 engine



V8 Vulcan engine, circa 1919

In 1902, Léon Levavasseur took out a patent on a light but quite powerful gasoline injected V8 engine. He called it the 'Antoinette' after the young daughter of his financial backer. From 1904 he installed this engine in a number of competition speedboats and early aircraft. The aviation pioneer Alberto Santos-Dumont saw one of these boats in Côte d'Azur and decided to try it on his 14-bis aircraft. Its early 24 hp (18 kW) at 1400 rpm version with only 55 kg (120 lb) of weight was interesting, but proved to be underpowered. Santos-Dumont ordered a larger and more powerful version from Levavasseur. He changed its dimensions from the original 80 mm stroke and 80 mm bore to 105 mm stroke and 110 mm bore, obtaining 50 hp (37 kW) with 86 kg (190 lb) of weight, including cooling water. Its power-to-weight ratio was not surpassed for 25 years. Levavasseur eventually produced its own line of V-8 equipped aircraft, named Antoinette I to VIII. One of these aircraft, piloted by Hubert Latham, tried but failed to cross the English Channel in 1909 due to the engine's gasoline injection. However, in 1910, the same plane with the same engine and the same pilot was first in the world to reach an altitude of 3600 feet. Voisin constructed pusher biplanes with Antoinette engines, also, notably the one first flown successfully by Henry Farman in 1908.

The V8 engine configuration became popular in France from 1904 onward, and was used in a number of aircraft engines introduced by Renault, and Buchet among others. Some of these engines found their way into automobiles in small quantities. In 1905, Darracq built a special car to beat the world speed record. They came up with two racing car engines built on a common crankcase and camshaft. The result was monstrous engine with a displacement of 1551 in^3 (25422 cc), good for 200 bhp (150 kW). Victor Hemery fixed that record on 30 December 1905 with a speed of 109.65 mph (176.46 km/h). This car still exists.

Rolls Royce built a 3,535 cc (216 cu in) V8 car from 1905 to 1906, but only 3 copies were made and Rolls Royce reverted to a straight-6 design. De Dion-Bouton introduced a 7,773 cc (474 cu in) automobile V8 in 1910 and displayed it in New York in 1912. It was produced only in small quantities, but inspired a number of American manufacturers to follow suit.

The first mass-production automobile V8 was introduced in the United States in 1914 by Cadillac, a division of General Motors which sold 13,000 of the 5,429 cc (331 cu in) L-head engines in its first year of production. Cadillac has been primarily a V8 company ever since. Oldsmobile, another division of General Motors, introduced its own 4 L (~244 cu in) V8 engine in 1916. Chevrolet introduced a 288 cu in (4.7 L) V8 engine in 1917, but after merging with General Motors in 1918, discontinued the V8 to concentrate on economy cars.

V angles

The most prevalent V angle for a V8 is 90°. This configuration features a wide, low engine with optimal firing and vibration characteristics. Many V6 and V10 engine configurations are derived from production V8 designs, they often use the 90° angle; however, balance shafts are incorporated to reduce vibration or more complex cranks to even the firing cycle. V8s can use different angles. One notable example is the Ford/Yamaha V8 used in the Ford Taurus *SHO*. It was based on Ford's Duratec V6 and shares that engine's 60° vee angle. A similar Yamaha-built engine is used by Volvo Cars as of 2005. These engines were designed for transverse front wheel drive installation and are narrower than usual for efficient use of space. Because they are not at the ideal 90° angle for a V8, they require a counter-rotating balance shaft and offset split crankpins for complete smoothness. In 2010, GM will introduce a 4.5 L Duramax diesel V8 with a 72° angle in which they state, "Considering manufacturing tolerances, a 72 V-8 engine can actually deliver better balance than a 90 engine." 72° V8's have been used in modern racing.

The Rover Meteorite V8 engine was derived from the Rover Meteor tank engine (hence derived from the Merlin aero engine), so shared the Meteor's 60° vee angle. In years past, Electro-Motive produced an 8-cylinder version of their model 567 Diesel locomotive engine, with a 45 degree cylinder angle. The 1932 Miller four-wheel drive race cars also featured a 45° V8.

An extremely narrow-angle V8 was introduced by Lancia in 1922, which had an angle between cylinder banks of only 14°. This created an engine that was shorter than a straight-6, but much narrower than a conventional V8. It was based on a Lancia V4 engine design that was almost completely "square" in the length and width of its layout. Because of their compact design and overhead camshafts, these engines were lighter and more powerful than comparable engines of the time. Although Lancia stopped making the V8 design around World War II, the basic concept is used today in the Volkswagen VR6 engine.

Crankshaft design

There are two classic types of V8s which differ by crankshaft:

- The **cross-plane** or two-plane crankshaft is the configuration used in most V8 road cars. The first and last of the four crank pins are at 180° with respect to each other as are the second and third, with each pair at 90° to the other, so that viewed from the end the crankshaft forms a cross. The cross-plane can achieve very good balance but requires heavy counterweights on the crankshaft. This makes the cross-plane V8 a slow-revving engine that cannot speed up or slow down very quickly compared to other designs, because of the greater rotating mass. While the firing of the cross-plane V8 is regular overall, the firing of each bank is LRLLRLRR. In stock cars with dual exhausts, this results in the typical V8 *burble* sound that many people have come to associate with American V8s, In all-out racing cars it leads to the need to connect exhaust pipes between the two banks to design an optimal exhaust system, resulting in an exhaust system that resembles a *bundle of snakes* as in the Ford GT40. This complex and encumbering exhaust system has been a major problem for single-seater racing car designers, so they tend to use flat-plane crankshafts instead.
- The **flat-plane** or single-plane crankshaft has crank pins at 180°. They are imperfectly balanced and thus produce vibrations unless balance shafts are used, with a counter rotating pair flanking the crankshaft to counter second order vibration transverse to the crankshaft centerline. As it does not require counterweights, the crankshaft has less mass and thus inertia, allowing higher rpm and quicker acceleration. The design was popularized in modern racing with the Coventry Climax 1.5 L (~92 cu in) V8 that evolved from a cross-plane to a flat-plane configuration. Flat-plane V8s on road cars come from Ferrari, (every V8 model they ever made, from the 1973 *308 GT4*, to today's *F430* and *California*), Lotus (the Esprit V8), and TVR (the Speed Eight). This design is popular in racing engines, the most famous example being the Cosworth DFV.

In 1992, Audi left the German DTM racing series after a controversy around the crankshaft design of their Audi V8 DTM. After using the road car's cross-plane 90° crankshaft for several years, they switched to a flat-plane 180° version which they claimed was made by "twisting" a stock part. The scrutineers decided that this would stretch the rules too far.

The cross-plane design was neither obvious nor simple to design. For this reason, most early V8 engines, including those from De Dion-Bouton, Peerless, and Cadillac, were flat-plane designs. In 1915, the cross-plane design was proposed at an automotive engineering conference in the United States, but it took another eight years to bring it to production. Cadillac and Peerless (who had hired an ex-Cadillac mathematician for the job) applied for a patent on the cross-plane design simultaneously, and the two agreed to share the idea. Cadillac introduced their "Compensated Crankshaft" V8 in 1923, with the "Equipoised Eight" from Peerless appearing in November 1924.

American V8 engines

De Soto Fire Dome V8 engine, at the 1952 LA Auto Show

A full decade after Britain's 1904 Rolls-Royce Legalimit, Cadillac produced the first American V8 engine, the 1914 *L-Head*. It was a complicated hand-built unit with cast iron paired closed-head cylinders bolted to an aluminum crankcase, and it used a flat-plane crankshaft. Peerless followed, introducing a V8 licensed from amusement park manufacturer, Herschell-Spillman, the next year. Chevrolet produced a crude overhead valve V8 in 1917, in which the valve gear was completely exposed. It only lasted through 1918 and Chevrolet would not produce another V8 until the introduction of the small block in 1955.

Cadillac and Peerless were one year apart again (1923 and 1924, respectively) with the introduction of the cross-plane crankshaft. Lincoln also had V8 cars in those years, as did Ferro, Northway (supplier to Cadillac, Cole Indianapolis, and Jackson, Mississippi), Perkins (Detroit), Murray, Vernon, and Yale. Oakland, a division of GM, introduced an 85 hp (63 kW) 250 cu in (4.1 L) V8 with a 180° crankshaft in 1930-1931. In 1932, the Oakland marque was discontinued and the V8 was used in its companion marque, Pontiac, for one year. Pontiac dropped the V8 engine in 1933 and replaced it with its smoother running Silver-Streak straight eight.

Ford was the first company to use V8s *en masse*. Instead of going to an inline six like its competitors when something larger than an inline four was needed, Ford designed a modern V8, the *Flathead* of 1932. This flat head engine powered almost all larger Ford cars through the 1953 production year, and was produced until around 1970 by Ford licensees around the world, with the valve-in-block engine powering mostly commercial vehicles.

After World War II, the strong demand for larger status-symbol cars made the common straight-6 less marketable. Straight-8 engines have problems with crankshaft whip and require a longer engine bay. In the new wider body styles, a V8 would fit in the same space as a straight-6. Manufacturers could simplify production and offer the bigger engines as optional upgrades to base models.

In 1949, General Motors (GM) responded to Ford's V8 success by introducing the *Oldsmobile Rocket* and *Cadillac OHV*. Chrysler introduced their *FirePower* 331 cu in (5.4 L) hemi-head V8 in 1951. That year Studebaker introduced its V8. Buick followed in 1953, while Packard and GM's Chevrolet and Pontiac introduced V8s of their own in 1955. American Motors initially purchased V8 engines from Packard, but developed its own lower-weight, 600 lb (272 kg), design in 1956.

Shelby Mustang GT350 V8 engine

A full history of each manufacturer's engines is outside of the scope, but engine sizes on full-size cars grew throughout the 1950s, 1960s, and into the early to mid-1970s. The increasing size of full-size cars meant smaller models of car were introduced and became more popular, with the result, by the 1960s, Chrysler, Buick, Ford, and Chevrolet had two V8 model ranges.

The larger engines, known as big-block V8s, were used in the full-size cars. Big-blocks generally had displacements in excess of 360 cu in (5.9 L), but in stock form are often not all that efficient. Big-block displacement reached its zenith with the 1970 Cadillac Eldorado's 500 cu in (8.2 L) *500*. Once the 1970s oil crisis and pollution regulations hit, big-block V8s did not last too much longer in cars; luxury cars lasted the longest, but by 1977 or so they were gone. In trucks and other larger vehicles, big-block V8s continue to be used today, though some manufacturers have replaced them with small-block-based V10s or more efficient Diesels. Big-block V8s are used in racing and such engines are available from independent engine builders. Some applications produce 2,000 hp (1,491 kW) from volumes exceeding 800 cu in (13.1 L).

Smaller engines, known as small-block V8s, were fitted in the mid-size car ranges and generally displaced between 270 cu in (4.4 L) and 360 cu in (5.9 L), though some grew as large as Ford's 408 cu in (6.7 L) *400 Cleveland*. There is overlap between big-block and

small-block ranges, and a factory engine between 6.0 and 6.6 L (366 and 403 cu in) could belong to either class. Engines like this (much evolved) are still in production.

A 4.0 L (244 cu in) V8 engine from an Oldsmobile Aurora

During the 1950s, 1960s and, 1970s, every GM division had their own engines, whose merits varied. This enabled each division to have its own unique engine character, but made for much duplication of effort. Most, like the comparatively tiny *Buick 215* and familiar *Chevrolet 350*, were confusingly shared across many divisions. Ford and Chrysler had fewer divisions, and division-specific engines were quickly abandoned in favor of a few shared designs. Today, there are fewer than a dozen different American V8 engines in production.

Lately, Chrysler and GM have designed larger displacement V8s out of existing modern small-block V8s for use in performance vehicles, such as Chrysler's 6.1 L (~372.2 cu in) and 6.4 L (~390.6 cu in) Hemis, and the LS7 7.0 L (~427.2 cu in) version of GM' LS engines.

Today, the major use for big V8s is in racing, where aluminum copies of the venerable Chrysler Hemi still dominate professional drag racing (Top Fuel Dragster and Funny Car).

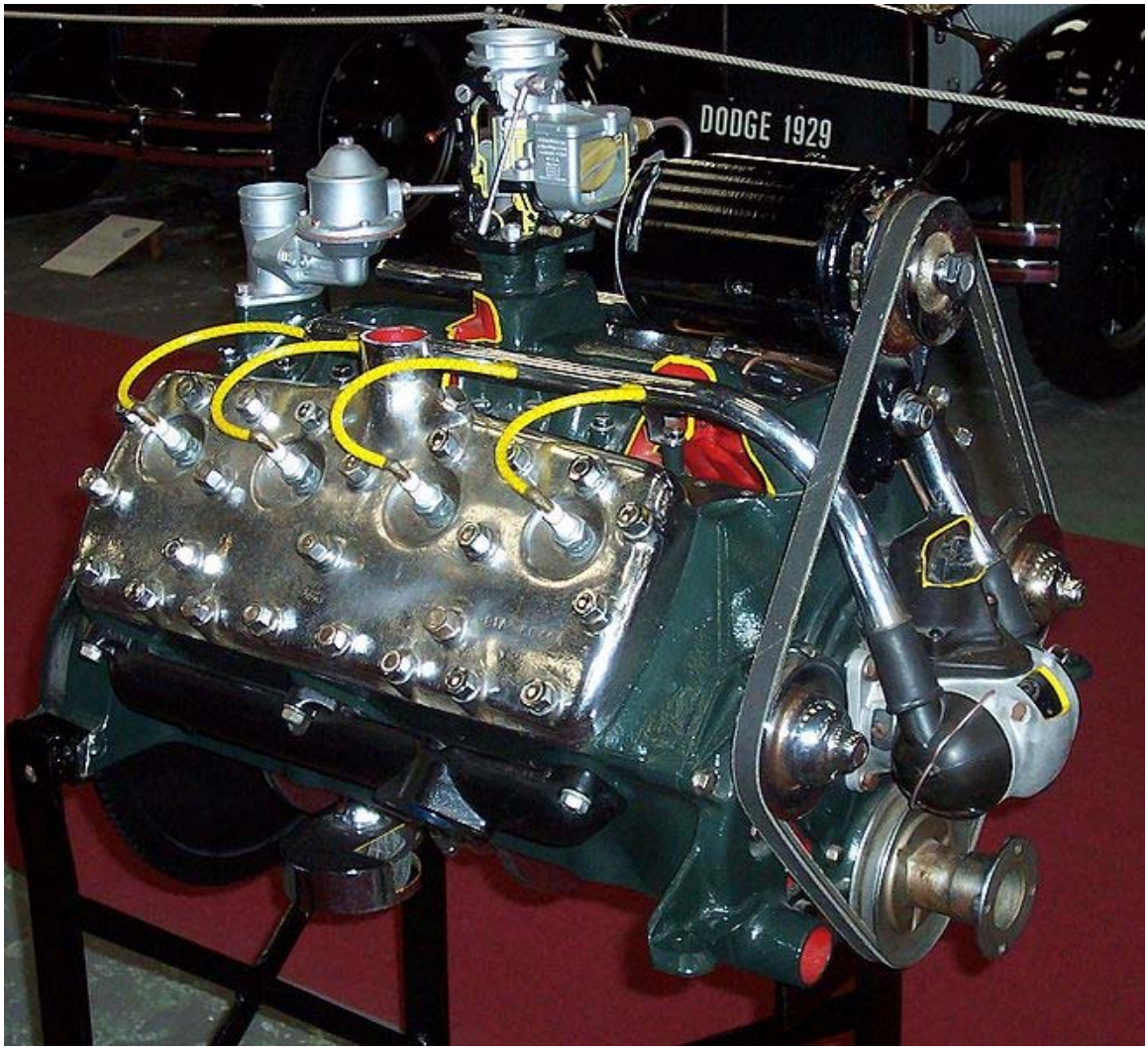
American V8s (by manufacturer and year)

A Supercharged custom V8 engine

- American Motors (AMC)
  - 1956-1966 GEN-1 Nash/Hudson/Rambler V8
  - 1966-1991 GEN-2 AMC and Jeep V8

- Chrysler
  - 1951–1959 FirePower
  - 1951–1958 and 1964–1971 Hemi (Original)
  - 1956–1967 A family
  - 1958–1971 B family
  - 1959–1978 RB family

- 1964–2003 LA Family
- 1999–present PowerTech
- 2003–present New Hemi



1930's flathead Ford V8 engine

- Ford
  - 1920–1932 Lincoln Liberty
  - 1932-1953 Flathead V8
  - 1954-1962 Y-block V8
  - 1958-1967 MEL V8
  - 1958-1976 FE V8
  - 1958-1982 Super Duty engine
  - 1962-2001 Windsor V8
  - 1966–present Cosworth DFV
  - 1968-1997 385 V8
  - 1970-1982 335/Cleveland V8

    - 1991–present Modular V8/Triton V8
    - 1996–present Jaguar AJ-V8
    - 1996–1999 Yamaha V8
    - 2004–present AJD-V8
    - 2009–present Lion V8
    - 2009–present Boss/Hurricane
    - 2011- Ford Coyote

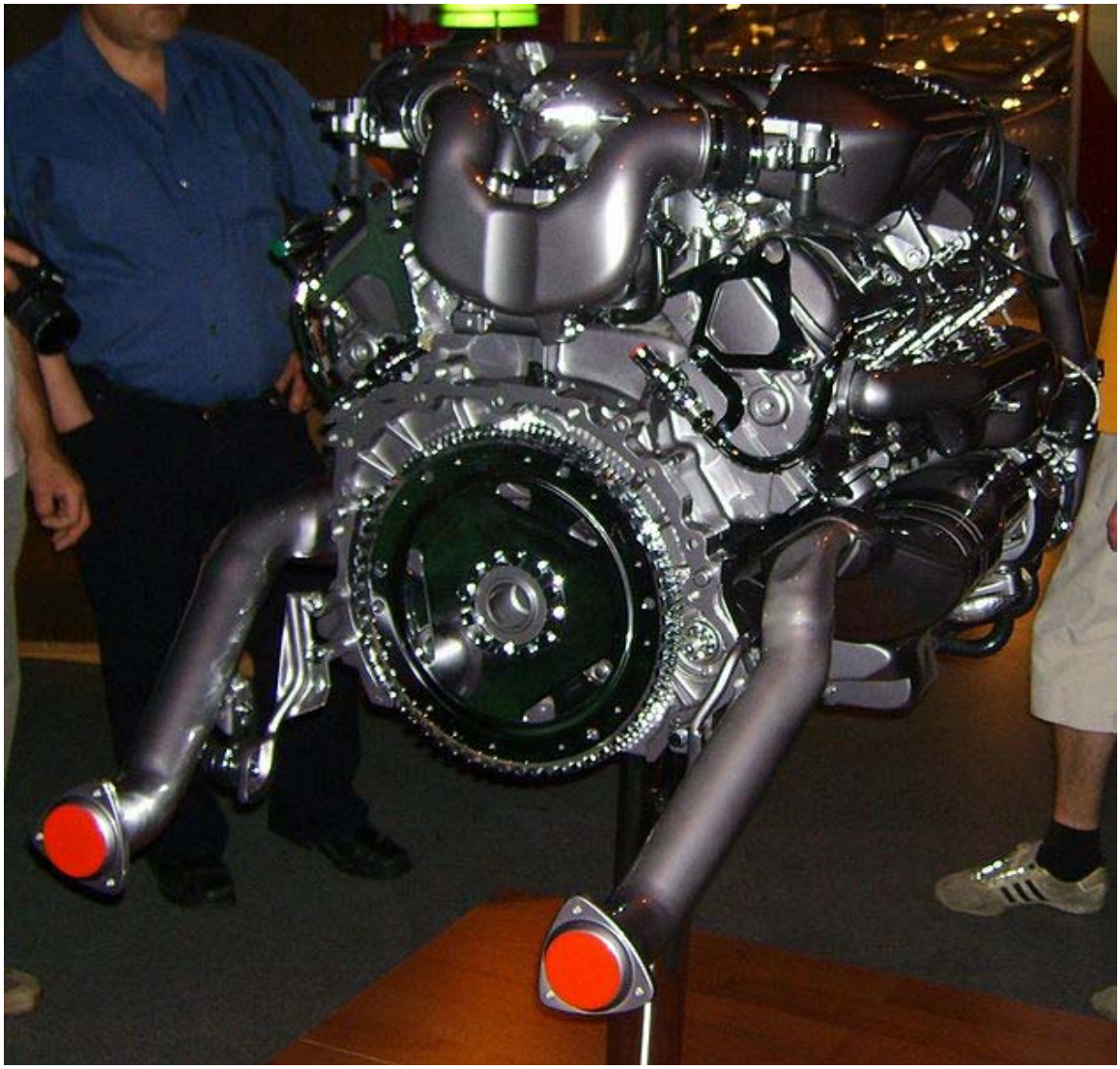
- General Motors
    - 1914-1992 Cadillac V8
    - 1930-1931 Oakland V8
    - 1932 Pontiac V8
    - 1949-1990 Oldsmobile Rocket V8
    - 1954-1970s Pontiac V8
    - 1950s-1970s Buick V8
    - 1954-2002 Chevrolet small-block V8
    - Chevrolet Big-Block engine
    - 1992–present Northstar/Premium
    - 1992-1997 Generation 2 small-block
    - 1997–present Generation 3 small-block
    - 2005–present Generation 4 small-block
    - Duramax Diesel

- Packard
    - 1955–1956

- Studebaker
    - 1951–1964

British V8 engines

1962 Coventry Climax FWMV 1500cc V8 Formula 1 engine in a Lotus 24



BentleyV8 engine

The first British V8 was the 3.5 L Rolls-Royce V-8 (1905) followed shortly by Darracq.

The Rolls-Royce and Bentley V8 still used in modern Bentleys was designed from 1952 and entered production in 1959 in the Rolls Royce Silver Cloud and Bentley S2. Following then current design practice, it featured overhead valves (OHV), a central camshaft and wedge-shaped combustion chambers. It was designed by the Rolls-Royce and Bentley Motors engineering team, led by Jack Phillips. Some of its were features inspired by the Rolls-Royce Merlin aircraft engine, including the aluminium block with wet liners, gear-driven camshaft, (initially) outboard spark-plugs and porting. Early versions were of 6.25 L (381 cu in) displacement, growing to 6.75 L (412 cu in) in the 1970s. Turbocharging in various Bentley models beginning in the 1980s led to the resurgence of the Bentley marque as the power outputs of the engine were increased in several steps to the current 500 bhp (370 kW) and 1,000 N·m (740 ft·lbf) in the 2007 model-year Bentley Arnage, while meeting all emission standards. The Bentley V8 has

thus increased power and torque by more than 150% in its life. It is the highest torque V8 used in a production car. In 2007, the final components that could be traced back to the 1959 engine were replaced.

In 1936, the Standard Motor Company introduced its 'Flying Twenty V-Eight' model featuring a 2.7 L flathead V8 developing 20 RAC horsepower. It was the flagship model of the company's 'Flying Standard' range but proved unpopular as it offered little performance improvement over the normal 'Flying Twenty' model (which used a straight-6 engine) whilst costing much more to buy and suffering higher fuel consumption. The Twenty V-Eight was on sale only for the 1936 model year and fewer than 400 were sold.

Rover was in need of a new, more powerful engine in the mid 1960s. The managing director of Rover, on a trip to the USA to sell marine engines, saw an example of the GM engine in a Mercury Marine experimental shop and noticed its light weight and small size. The 215 cu in (3,520 cc) GM V8 was only 12 pounds (5.4 kg) heavier and less than 1 inch (2.5 cm) longer than the 2,000 cubic centimetres (120 cu in) Rover straight-4 and sent the GM Oldsmobile/Buick cast-aluminum *215* V8 back to the UK for evaluation. It worked well in the large Rovers, being considerably shorter, lighter, and more powerful than the Rover straight 6, and Rover acquired manufacturing rights to it. The Rover V8 was redesigned to improve the durability and high-RPM performance, leaving few parts interchangeable with the original Buick engine. The engine first appeared in Rover saloons in the late 1960s. GM aided the process by allowing Buick's chief engine designer, who was close to retirement, to assist Rover.

As well as appearing in Rover cars, the engine was also sold to small car builders, and powered various vehicles. Rover V8s feature in some models from Morgan, TVR, Triumph, Marcos, and MG, among others. The Australian firm Repco converted this engine for Formula One by reducing it to 3.0 L (183 cu in) (the stroke was shortened and using con-rods from the 2.5 L/153 cu in Daimler V8) and fitting a single overhead camshaft per bank rather than the shared pushrod arrangement. Repco-powered Brabhams won the F1 championship twice, in 1966 and 1967. Land Rover also used the V8, appearing in the Range Rover in various guises, from 3.5 L (~214 cu in) in the earlier models to the 4.6 L (~281 cu in) used in the 1994-2002 models. The last mass-produced car to use the Rover V8 was in some models of the Land Rover Discovery, up to 2004. Many independent sports cars manufacturers still use it in hand-built applications.

Recently Land Rover (Tata) added the TDV8 to its list of engines. It is a V8 version of the popular TDV6 found in Discovery models. This diesel engine will be found in the 2007 Range Rovers. This 3.6 L (~220 cu in) engine produces 472 ft·lbf (640 N·m) at 2000 rpm.

The Rover Meteorite petrol or diesel V8 was used in trucks and transporters from 1943, and for marine or stationary use.

Triumph used the Triumph Slant-4 engine as a base of a V8 engine. The Triumph V8 was used only in the Triumph Stag.

Edward Turner designed the 2.5 L (~153 cu in) and 4.5 L (~275 cu in) hemi-head Daimler V8 engines announced in 1959. The 2.5 saw service in the Daimler SP250 (1959–1964), and, after the Jaguar takeover, in the "Daimler 2.5 Litre V8"/"Daimler 250" (1962–1969) versions of the Mk2 Jaguar bodyshell. The 4.5 was used in the Daimler Majestic Major, (1959–1968).

The Jaguar company introduced the new AJ26 V8 engine in 1996. It has been developed and updated since, and appears in the S-Type and later vehicles from Jaguar. This V8 was used in some of Ford's Premier Automotive Group Jaguar and Land Rover brands. These included a 4.2 (Jaguar XJ, XK and S-Type), 4.2 supercharged (Jaguar XJR, XKR, S-Type-R, Land Rover Range Rover and Range Rover Sport) and a 4.4 (Range Rover and Range Rover Sport). New V-configuration engines are used since the buy out by the Tata Motor group.

The specialist sports car firm TVR also produced their own V8 engine in 4.2 L (~256 cu in) 350 bhp (261 kW) and 4.5 L (~275 cu in) 440 bhp (328 kW) liter forms for the TVR Cerbera. Designed by Al Melling, the APJ8 engine features a flat-plane crank and 75° Vee.

Aston Martin has used a variety of V8 engines in its cars, starting with the 1969 DBS V8, followed by many models badged V8 Vantage, or Virage, plus Volante convertible versions. After the Vantage was discontinued in 2000, there were no V8 models until the introduction of the Jaguar derived 4.3l V8 in the 2005 V8 Vantage. The V8s used in Aston Martins from 1969-2000 were based on an internal design by Tadek Marek, while the V8 engines used in the 2005–present V8 Vantage are based on the Jaguar AJ26 V8.

Lotus introduced a V8-powered version of the Esprit in 1996. The engine was an in-house 3.5 L (~214 cu in) unit, with twin turbochargers.

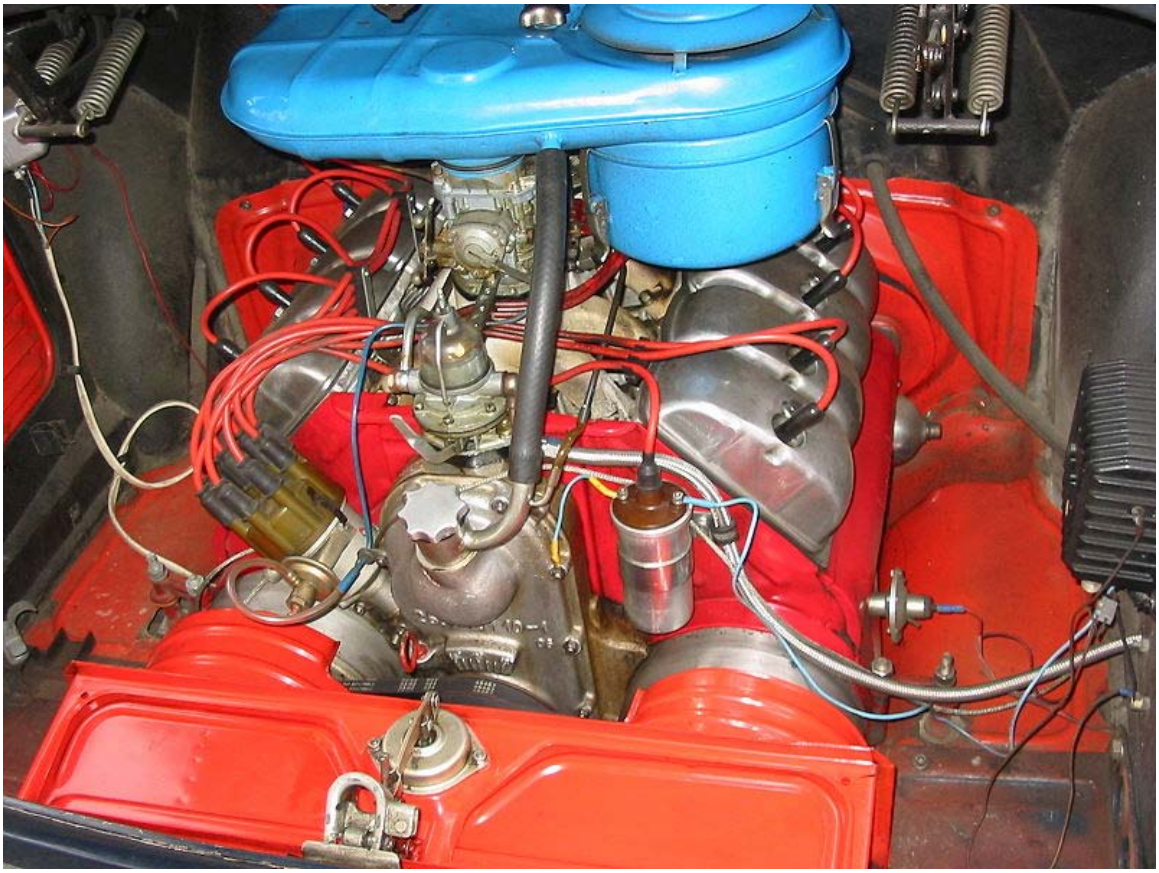
Radical Sportscars offer a V8 powered car, the SR8, whose Powertec RPA engine is based upon two Suzuki Hayabusa engines joined to a common crank, utilising the original heads with a purpose designed block.

In 2010, McLaren Automotive developed M838T 3.8-litre V8 twin-turbo engine, used in MP4-12C

Chinese V8 engines

- FAW Hongqi by First Automobile Works
  - CA72
  - CA770
  - HQ430

Czech V8 engines



Tatra T603 engine

Tatra used air-cooled V8 engines. These culminated in the 2.5 L unit used in the Tatra T603 range of cars. The most powerful of these was fitted to the racing variant — known as the B-5. This was a higher compression version of the standard engine which replaced a standard single 2BBL carburettor with two 4BBL downdraft units on a new induction manifold. Tatra later produced another air-cooled engine, used in Tatra 613 and later, in Tatra 700. These engines were well known for their reliability, good fuel consumption, and specific sound.

In the Tatra 603, two engine driven fans help pull cooling air into the engine bay — when the vehicle is in motion the air enters through intakes in the rear wing panels and is exhausted through cut-outs below the bumper and alongside the engine itself. In the Tatra 613, one large ventilator pushes fresh cold air into the engine bay.

Tatra has used V8 air cooled engines in their heavy duty trucks until the present day in their Tatra 815 and other models.

- T77 1934-1938 - 3.0 Litre air cooled V8
- T87 1936-1950 - 3.0 Litre air cooled V8
- T607 Monopost - 2.35 Litre V8

- T603 1956-1975 - 2.5 Litre air cooled V8
- T613 1974-1996 - 3.5 Litre air cooled V8
- T700 1996-1999 - 3.5 or 4.4 Litre air cooled V8
- T815 1983-now - 12.7 Litre air cooled V8

French V8 engines

Prototype V8 engine for the Peugeot 802

The French De Dion-Bouton motorcar firm was first to produce a V8 engine for sale in 1910. Later examples came from Citroën, with the never produced 1934 22CV *Traction Avant*, and Simca. Peugeot's upcoming 608 and its Citroën C6 stablemate may have a new HDi 4.0–5.0 L (240–310 cu in) V8 as well as a possible petrol 3.6 and 4.4 L (220

and 270 cu in) V8. The "PRV" (Peugeot, Renault, Volvo) V6 was actually supposed to be a V8, but two cylinders were "dropped" because of the oil crisis of the 1970s. Gordini also developed a 3 L V8 for the Alpine A310, but a Renault 4-cylinder block was mounted instead because of cost issues.

German V8 engines

BMW S65 4.0L V8 Engine

German V8s (by manufacturer and date)

- Audi
  - 1988–present V8 engine

- BMW
  - OHV V8 1954-1965
  - M60 1992-1995
  - M62 1994-2005
  - S62 1998-2003
  - N62 2002–present
  - S65 2007–present
  - M67 1998–present

- Horch
  - 830, 930 1933-1940

Mercedes-Benz M156 AMG 6.3L V8 DOHC Engine

- Mercedes-Benz
  - 1965-1979 M100
  - 1971-1991 M117
  - 1981-1991 M116
  - 1990-1999 M119
  - 1999–present M113
  - 2004–present M155
  - 2006–present M273
  - 2006–present M156
    - OM402 Diesel
    - OM422 Diesel

- Porsche
  - Porsche 928 1978–1995
  - Porsche Cayenne 2002–present
  - Porsche Panamera 2009–present

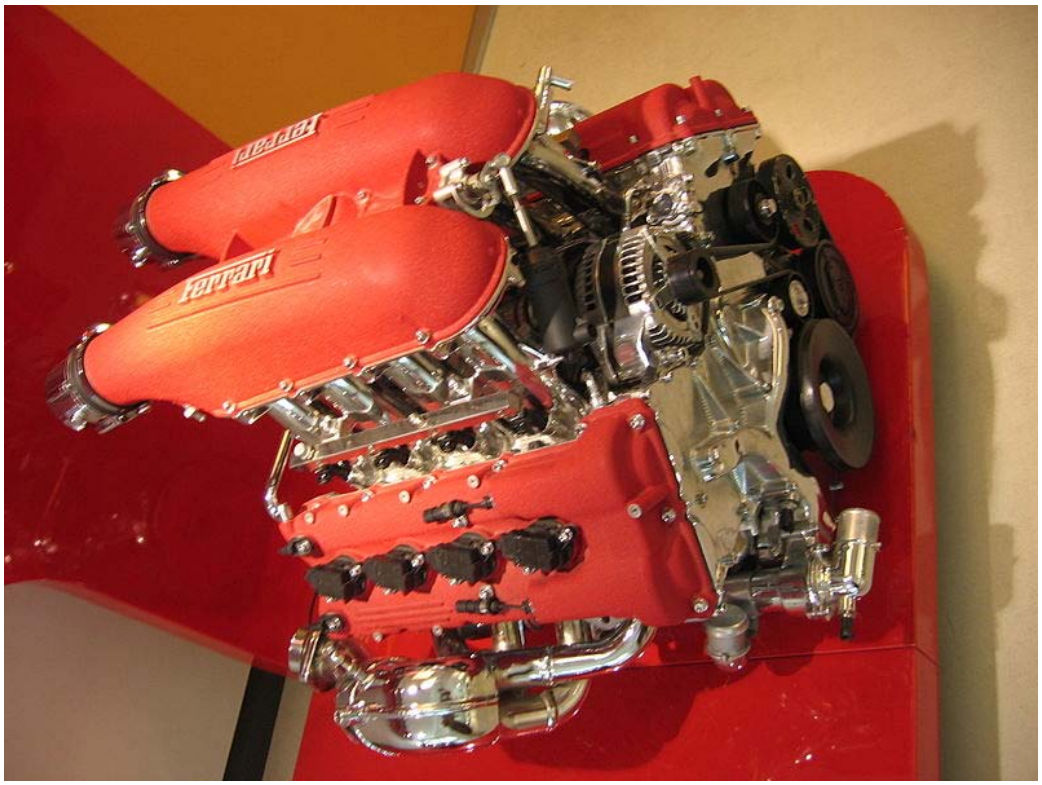
- Stoewer
    - Greif V8 1934-1937

Italian V8 engines

Alfa Romeo

The Alfa Romeo Montreal was powered by a dry sump 2,593 cc (158.2 cu in) 90° quad-cam 16-valve V8 (type 00564) derived from the Tipo 33 race car. Because of the limited space available for the cross-plane crankshaft, the physically small but heavy crank counterweights were made of a sintered tungsten alloy called turconit. The Montreal V8 was rated at 230 horsepower (170 kW) at the flywheel and weighed 162 kg (360 lb). There were also eighteen 33 Stradale cars built with a detuned 1,995 cc 260 hp (190 kW) Tipo 33/2 flat-crank engine. The Montreal cross-crank engine was also used in a very limited production run of 22 Alfetta GTV2.6i. The Alfa Romeo 8C Competizione sports car has a Ferrari-built 4,691 cc (286.3 cu in) 450 PS (330 kW; 440 hp) cross-crank V8.

Ferrari



Ferrari V8, 4,300cc

Arguably, Ferrari had their first contact with V8 power with the "inherited" Lancia D50s in 1955. Ferrari adopted the V8 configuration for themselves for racing in 1962 with the 268 SP. The first V8-powered Ferrari road car was 1974's 308 GT4, with the familiar 308 GTB following closely behind. The company continued to use this *Dino* V8 engine ever since with the 328, 348, and successors. Ferrari's smallest V8 (and indeed, the smallest ever) was the 2.0 L (1990 cc) unit found in the 1975 208 GT4. The company produced a slightly-larger 2.0 L V8 in the 208 GTB and the 2.9 L Ferrari F40 of the 1980s. Five-valve versions of Ferrari's 3.5 L and 3.6 L V8s were found in the Ferrari F355 and Ferrari 360. The old *Dino* V8 was retired for 2004 with the introduction of a 4.3 L V8, based on the originally Ferrari designed Maserati 4.2 V8, in the F430. And F430's successor, 458 Italia, with 4.5 V8.

Fiat

The only Fiat to have a V8 was the Fiat 8V. The engine was a very compact OHV 1996 cc (122 CID) V8 with a 70° V angle and 2 valves per cylinder. The Fiat 8V was designed to participate in the Italian two-litre racing class.

Lamborghini

Lamborghini have always fitted V12s in their top-of-the-line cars, but have built many V8s for their lower models, including the Urraco, Silhouette and Jalpa.

Lancia

Lancia used V8 engines in their top of the range luxury cars in the interwar period. The first V8 engine was available in 1922 in the Trikappa with a 4595 cc (280 CID) making 98 bhp (73 kW). In 1928 they introduced the Dilambda with a 3956 cc (242 CID) V8 developing 100 bhp (75 kW). Later in 1931 the Astura was unveiled with two smaller versions of the existing V8, 2604 cc (159 CID) and 2973 cc (181 CID) with 72 bhp (54 kW) and 82 bhp (61 kW) respectively. All of those engines featured Lancia's trademark narrow angle V (less than 25°). In the 1990s, Lancia Thema had 3 L V8.

Maserati

Maserati have used V8s for many of their models, including the Maserati Bora and the Maserati Khamsin. This engine was initially designed as a racing engine for the Maserati 450S. The company's latest 4.2 V8, found in the Maserati Quattroporte and Maserati Coupé & Spyder was originally designed by Ferrari, and is related to the 4.2l V8 in the F430.

Japanese V8 engines

Japanese manufacturers are traditionally not known for V8 engines in their roadcars. However, they have built a few V8 engines to meet the needs of consumers, as well as for their own racing programs.

Honda

Honda has never built a V8 for passenger vehicles. In the late 1990s, the company resisted considerable pressure from its American dealers for a V8 engine (which would have seen use in top-of-the-line Honda SUVs and Acuras), with American Honda reportedly sending one dealer a shipment of V8 beverages to silence them.

However, Honda has built V8s for racing, most notably for Formula One. Honda is also the sole engine builder for Indy Racing. The Honda Indy V-8 has a 10,300 rpm redline. Also, their affiliate Mugen Motorsports (now known as M-Tec) has built racing V8s that eventually found their way into limited production road cars as well as concept cars. Their MF408S engine, which powers cars in the ALMS, is also found in prototype racers such as the Mooncraft Shiden. It is also known for being the engine in the Honda Legend based Honda Max concept.

Mitsubishi

In 1999, Mitsubishi Motors developed an alloy-headed 4.5 L V8, dubbed the 8A8, with double overhead camshafts and gasoline direct injection (GDI) technology for use in its Proudia and Dignity models. Financial pressures forced the company to discontinue sales of both these vehicles after only fifteen months

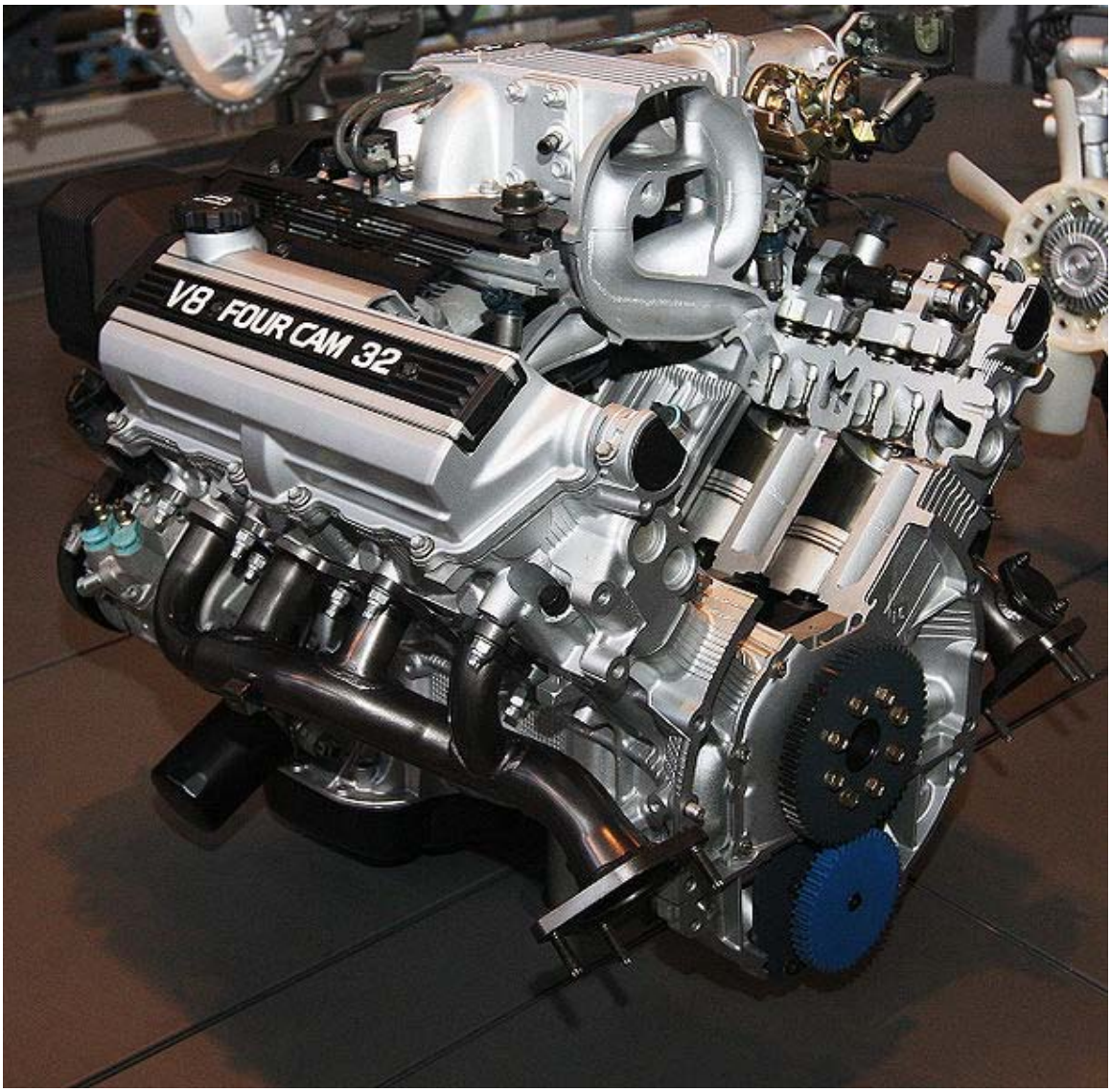
Nissan

2008 Nissan VK50VE engine. V8 5,026cc

Nissan built its first V8, the Y40, in 1965 for its President limousine. The Y engine has been succeeded by two families of V8, the VH series during the 1980s and 1990s and the new VK series.

- VK engine
- VH engine
- Y engine

Toyota



1989 Toyota 1UZ-FE Type engine. V8 3,968cc.

Toyota's first V8 engine family was the V series used in the Toyota Century luxury car. This engine remained in use in the Century until it was replaced by a V12 in 1997. Other Toyota V8 families are the UZ engines and the new UR engines.

- UR engine
- UZ engine
- V engine

Yamaha

1989 Yamaha OX88 engine

While better known as a manufacturer of motorcycles, Yamaha also makes engines under contract from auto-manufacturers. They currently produce a V8 engine in conjunction with Volvo Cars for vehicles such as the Volvo XC90 and the Volvo S80.

Swedish V8 engines

2005 Volvo (Yamaha) V8 engine for Volvo XC90. V8 4,414cc

The most well-known Swedish V8 engine is probably the Scania AB 14 L (854 cu in) diesel, which was released in 1969 for use in the 140 model heavy trucks. At this point, the 350 hp (261 kW) turbo-charged engine was the most powerful diesel in Europe. Scania has continued using a V8 as its largest displacement engine. Currently a series of 16 L (976 cu in) diesel engines is available in several versions with power ranging between 500 hp (373 kW) — 730 hp (544 kW) in the truck segment and going as high as 900 hp (671 kW) in the marine engines segment. Emission norms range between Euro 3-Euro 5 depending on which market the vehicle is sold to.

Volvo's 1950s concept car Philip also had a gasoline V8 engine. The car never went into production, but the engine evolved into a 120 hp 3.6 L V8 (in many aspects a "double B18" engine) for use in the light trucks Volvo Snabbe and Volvo Trygge from the late 1950s on.

Supercar manufacturer Koenigsegg has developed a 4.7 L (~287 cu in) twin-supercharged V8 loosely based on the Ford Modular engine. This engine is unique in that it is a flexible fuel engine and produces more power while running on biofuel than on regular unleaded.

Russian V8 engines

ZIS, ZIL

For the ZIL-111 (1959), an all-new aluminium 6 L OHV V8 was developed, initially it produced 200 hp (149 kW) at 4200 rpm.

ZIL-114 (1967) was powered by a 6,960 cc (425 cu in) V8 giving 300 hp (224 kW) at 4400 rpm. Its more modern derivative model, the ZIL-41047, is powered by a ZIL-4104 engine, a 7680 cc carburetted V8 giving 315 hp (235 kW) at 4600 rpm.

The ZIL trucks used (and still use) a modification of this engine (cast-iron block, aluminum heads, 6L, 150 hp (112 kW) at 3200 rpm, 6.5:1 compresson rate, one 2-bbl carburetor).

GAZ (ZMZ)

GAZ-24-34 Volga with ZMZ-503 V8 engine, 1992-built car.

Several cars produced under the Volga brand name; the GAZ-23 (1962–1970), the GAZ-24-24 V8 (1974–1992), the GAZ-31013 V8 (1982–1996), as well as both generations of the GAZ Chaika limousines (1959–1982 and 1976–1988) were powered by an all-aluminum OHV 5.5L V8. These engines were designated: ZMZ-13 (Chaika GAZ-13, one 4-bbl carburetor), ZMZ-14 (Chaika GAZ-14, two 4-bbl carburetors), ZMZ-2424 (Volga GAZ-24-24), ZMZ-505 (two 4-bbl carburetors) and -503 (one 4-bbl carburetor) (GAZ-24-34, GAZ-31013). Power output varied from 195–220 hp (145–160 kW). A modification of the same engine was also used in the BRDM-2 military armored vehicle, designated ZMZ-41.

The GAZ-53 was powered by a 4254 cc ZMZ-53 engine, which substantially was a modification of the Chayka's engine with one 2-bbl carburetor and decreased displacement and compression rate. More modern version of the GAZ engine for intermediate trucks is designated ZMZ-511.

Spanish V8 engines

Spanish truck and sportscar company Pegaso made around 100 cars in the 1950s and 1960s. There were two types of engines; the Z-102 and the Z-103/4 engines.

The Z-102 first introduced in 1951 engine was an advanced design sporting quadruple camshafts (two per bank) and had 2 valves per cylinder. It was available with 1, 2 or 4 twin Weber carburettors and either normally aspirated or with one or two superchargers. It had three different capacities, 2472 cc (151 CID), 2816 cc (172 CID) and 3178 cc (194 CID) and made between 165 bhp (123 kW) and 360 bhp (270 kW).

The Z-103/4 developed in the mid/late 1950s (the first prototype was made in 1954) was a much simpler design destined to power a new series of luxury and sportscars. It had a single central camshaft and 2 valves per cylinder actuated by pushrods. It had hemispherical combustion chambers (like the Z-102 engine) and twin spark plugs. It was available with three different cubic capacities as well, 3900 cc (238 CID), 4500 cc (275 CID) and 4700 cc (287 CID). The 3.9 L engine had a twin Weber carburettor and the 4.5 and 4.7 L engines 2 quadruple Weber carbs, which gave the later a power output in excess of 300 bhp (220 kW). The very few engines of this type produced were installed in Z-102 cars.

Australian V8 engines

Holden, including its performance vehicle operations Holden Racing Team and Holden Special Vehicles, have been manufacturing V8 performance vehicles since the late 1960s, as has Ford Australia. The performance arm of Ford Australia, Ford Performance Vehicles (FPV), have recently resurged in the market with the new Falcon BA and BF based models, and the brand new FG series.

The Australian V8 is typically an American-manufactured block from either Ford, Chrysler or General Motors yet often uses local heads and auxiliary systems (pistons, exhaust etc.). However, there are a couple of exceptions to this — the Holden V8 engine small block V8, and the British Leyland alloy small-block V8.

The Holden small-block V8 was an all Australian designed and manufactured cast-iron 90° pushrod OHV engine, manufactured in the capacities of 4.2 L (253 CID), 5.0 L (308 CID), later destroked to 304 CID), and 5.7 L (348 CID — never actually built as a 'production' motor). First introduced in 1969, finally ceasing production in 1999, it powered a variety of Holden vehicles including the Kingswood, Monaro, Torana and Commodore, and proved to be a popular and successful powerplant in Australian motorsport (especially Touring cars).

The British Leyland small block V8 was also a pushrod OHV engine, however it was an all alloy block like the British Rover V8 it was based on. The stroke was increased to give it a capacity of 4.4 L (270 cu in). The motor was originally designed and fitted to the Leyland P76 sedan.

Currently, the only V8 produced in Australia is the 5.4l V8 built by FPV (Ford Performance Vehicles) to power the Falcon GT — this motor is a combination of US-sourced and locally manufactured parts. The V8 used in current Holdens is sourced complete from GM in Canada, modified versions of the GM LS-series engine.

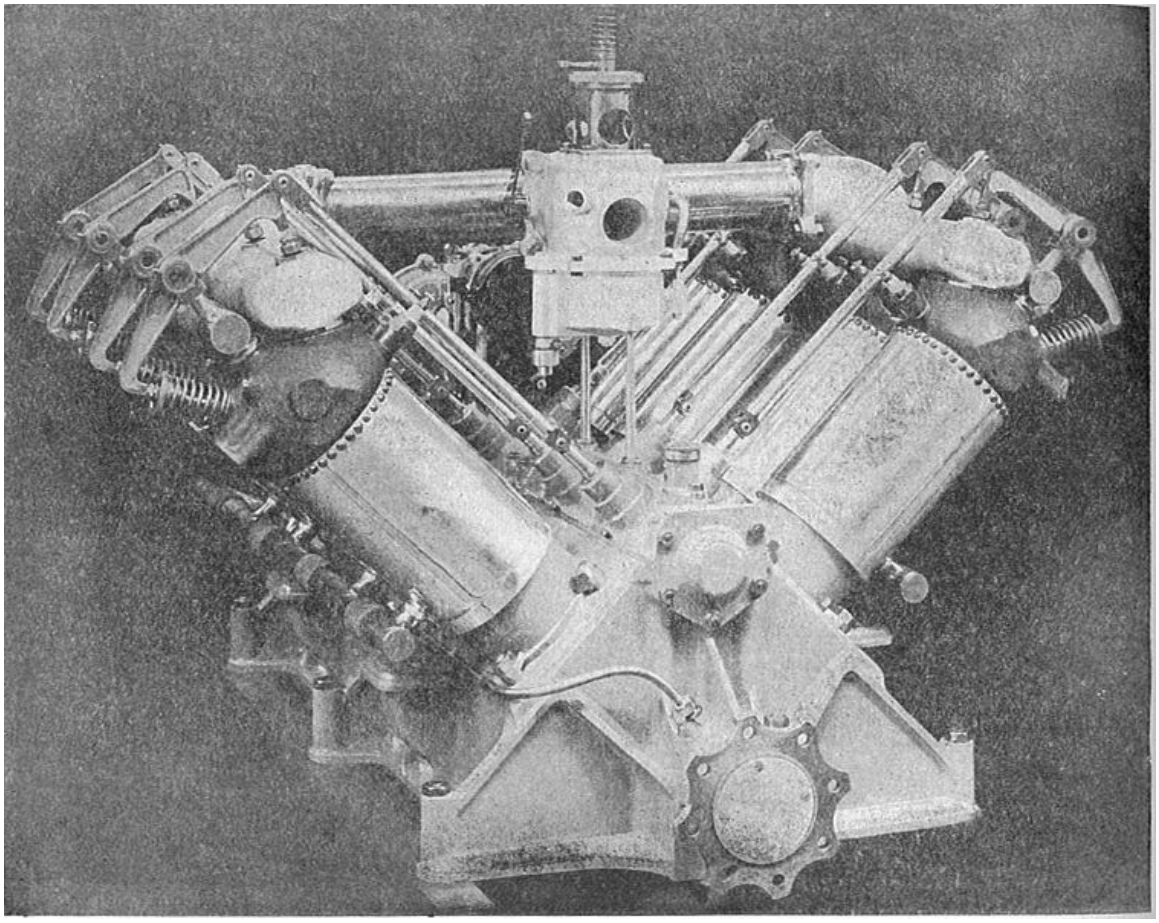
When U.S. production of the Cleveland V8 range ceased in the early seventies, the tooling was moved to Australia where Ford Australia continued to produce a local version of the 351 and a unique-to-Australia 302 Cleveland. The Australian-built motors were also sold to De Tomaso to be used in the Pantera and Longchamps. Australian production ceased in 1982, with the last Cleveland-powered Falcon being the XE range (1400-odd 302s and 409 351s). The location of the Cleveland tooling is unknown although it was possibly broken up.

Korean V8 engines

- Hyundai
  - D8 - 16/18 L-Diesel
  - Omega - 4.5 L (~275 cu in)
  - Tau - 4.6 L (~281 cu in)

Other V8 applications

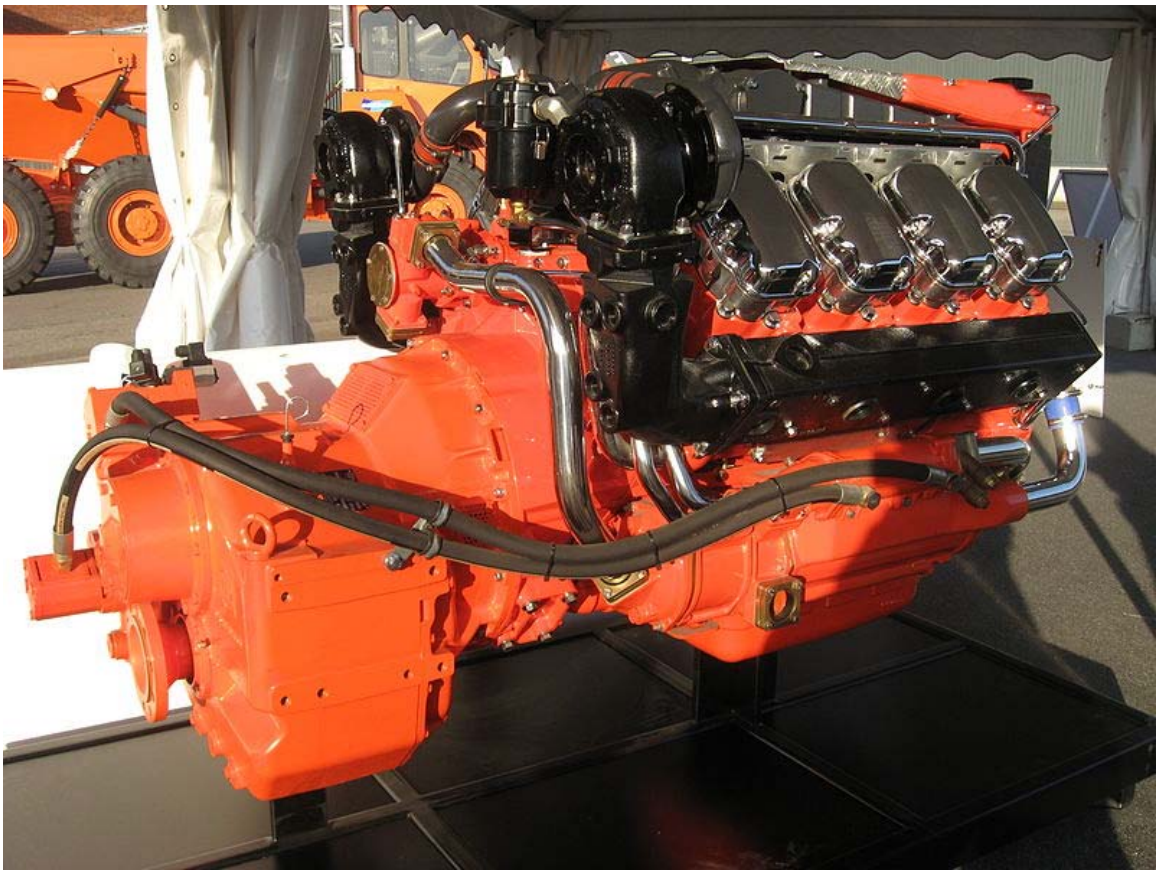
In aviation



1905 Wolseley 120 hp V8 aero engine

- Argus As 10 inverted, air-cooled German V8 engine of World War II.
- Hispano-Suiza 8 of World War I V8.
- Liberty L-8 of World War I, 45° V8 (a prototype for the Liberty L-12).
- Renault of WW1, 240 hp (180 kW) V8
- Trace Engines Turbocharged V8.

Ship's engines

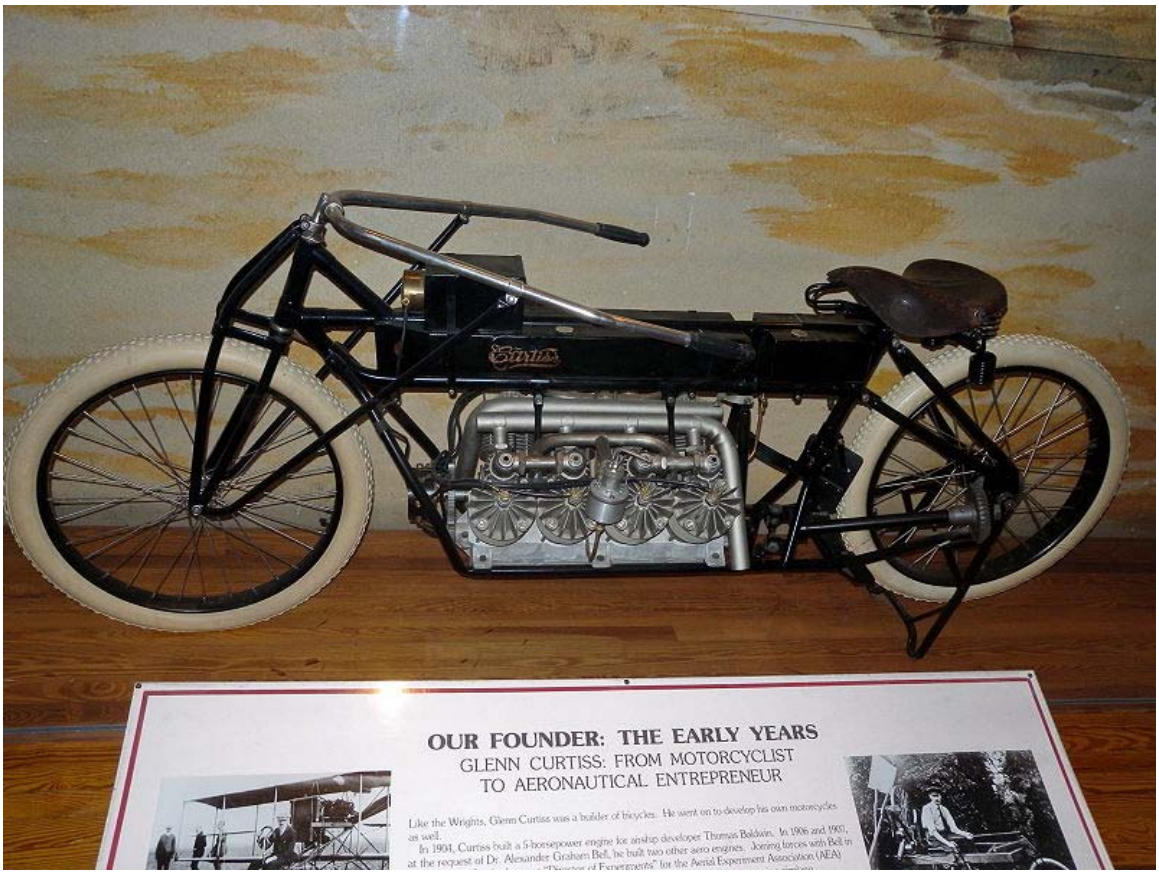


Scania V8, 16 litre marine engine with reverse.

There are numerous marine diesel engines of V8 configuration.

- Brons V8 two-stroke diesel engine.
- Scania
- Yanmar

In motorcycles



V8 Motorcycle of Glenn Curtiss. In 1907, Curtiss set an unofficial world record of 136.36 mph (219.45 km/h) on this 40 hp (30 kW), 4,000 cc V8 powered motorcycle of his own design and construction

Moto Guzzi of Italy built a 148 kg (330 lb) 82 bhp (61 kW) water cooled DOHC V8 4-stroke motorcycle for Grand Prix racing between 1955 and 1957, referred to as the Moto Guzzi Grand Prix 500 cc V8. It was known as the *Otto Cilindri,* and had a very high power output but was not developed to its full potential. Each cylinder had its own carburetter.

Morbidelli produced an 848 cc V8 in 1994. Earlier, Galbusera had produced a two-stroke V8 in 1938.

Honda released the NR750 in 1992. The bike had a 750 cc V4 with oval pistons, utilising 8 valves per cylinder and 2 conrods per piston; the design allowed the engine to meet FIM racing regulations limiting the number of cylinders to 4, while providing the valve area (and therefore increased efficiency) of a V8.

In motorsport

A 2004 Cosworth Champ Car World Series V-8 engine, capable of generating over 800 horsepower from just 161 cu./in

Renault F1 RS26 (2006), 2,398cc V8 engine

Up until recently, Formula One cars used 3 L V10 engines. However, the FIA considered speeds were getting too high to be safe (even with the banning of turbochargers in 1989, which allowed engines to develop 1,300 bhp (970 kW), 1,000 bhp (750 kW) from a naturally-aspirated engine was not impossible by 2005, and with better aerodynamics, cars were shattering straight-line speed records.) So, the permitted engine size was cut to 2.4 L V8 (This reduced average power output of the engines from 900 bhp (670 kW), in the 2005 season, to a 2006 season average of 750 bhp (560 kW) — equivalent to power outputs that were being achieved on 3 L around the 1999/2000 seasons.)This also had the effect of reducing overall costs for the teams, an aim which is currently being vigorously pursued by FIA.

In the 'Top Fuel' class of Drag Racing, V8 engines displacing 8.2 L or 500 in³ produce up to 8,000 horsepower (6,000 kW). Based on the Chrysler Hemi and running on highly explosive Nitro-Methane fuel, these powerful units propel the cars from 0-100 mph in 0.8 seconds or less, and from 0–325 mph (0–523 km/h) in under 4.5 seconds. During the race the crankshaft in the engine will turn over less than 1000 times and may then have to be rebuilt.