50 YEARS OF PORSCHE FLAT-SIX ENGINES

Porsche has been building flat-six engines for 50 years. During this time, the design concept has repeatedly been adapted to the changing requirements, thus ensuring that the advantages inherent in the concept could continue to be used. In the following report, the company compares characteristic design features of the historic engine with those of the current version.

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DESIGN ADVANTAGES AND HISTORY

Porsche is celebrating the 50th anniversary of the Porsche 911 and the 50th anniversary of the flat-six engine together. Not for the sake of tradition, but because of its design advantages. It is particularly flat, lightweight and compact, and therefore the ideal engine type for a sports car. The flat-six engine runs smoothly and does not generate so-called free torques or forces. Furthermore, flat engines are ideal for reducing the centre of gravity of a vehicle. The horizontal cylinders allow a particularly low design and the lower the centre of gravity of a vehicle is, the more sportily it can be driven.

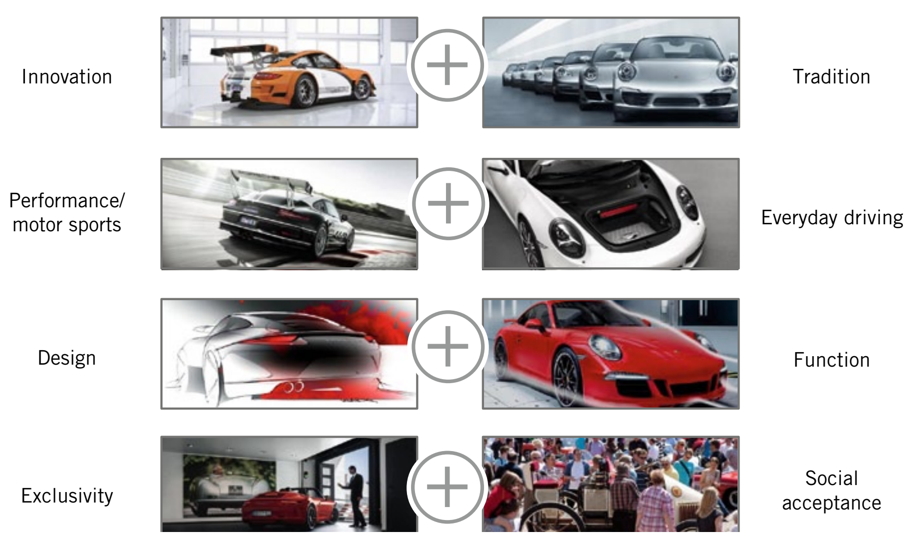
One of the most prominent features of Porsche flat-six engines has always been their low fuel consumption relative to engine power. This outstanding efficiency results from the overall concept, which is inspired by the world of motor sport. It is based on consistent lightweight construction, high revving ability and high specific power achieved through an advantageous gas cycle.

Over the last 50 years, a number of conflicting objectives have come to light during the development of a new 911, ❶. A new Porsche must always be more innovative and deliver higher performance than its predecessor in all areas. It must exhibit a design which accentuates these characteristics while also preserving tradition and meeting the exclusive demands of our customers. At the same time, social acceptance must be retained. The achievement of optimal fuel consumption values and compliance with all legal limits go without saying. Furthermore, the balancing act between day-to-day usability and sportiness must be mastered. A 911 should always set new standards in both characteristics.

The first 911 demonstrated this most impressively as early as 1963. The 901/911 flat-six engine produced a power output of 96 kW at 6100 rpm from a displacement of 2.0 l. After model year 1967, the 911 S variant with performance enhancement had a power output of 118 kW at 6600 rpm. There was also the 911 T, which was designed as an entry model and had a reduced power output of 81 kW at 5800 rpm [1]. In 1973, the displacement of all engines in the 911 range designated as the "G model" generation was increased to 2.7 l [1].

In 1974, another new development made its first appearance when Porsche presented the 911 Turbo, the first production sports car to be equipped with a turbocharger. The engineers applied extensive experience gained from the world of motor sport to transfer the technology of turbocharged engines to series production vehicles. Based on the engine in the 911 Carrera RS 3.0, the engine produced 191 kW and 343 Nm of torque, and achieved a top speed of more than 250 km/h (155 mph) [1].

The enhancement of the six-cylinder engine brought an increase in the displacement and power output over several stages, combined with the latest emission control technology. Porsche constructed the first flat engines with con-



❶ Conflict of objectives

trolled catalytic converter in 1980. Three years later, a new generation of naturally aspirated engine with a 3.2 l displacement and digital engine electronics was presented. All engines were now prepared for regular unleaded fuel. In 1988, Porsche further enhanced combustion in the engine and developed a cylinder head with two spark plugs in each combustion chamber [1, 2, 3].

The air-cooled flat engine reached its zenith with the naturally aspirated engine from the 993 model line, which produced 221 kW from a displacement of 3.8 l in the 911 Carrera RS top-of-the-range model in 1995. Derived from motor sport, the 911 GT2 was manufactured in a limited production run with a 3.6-l engine and two turbochargers, which initially produced 316 kW in model year 1998 and then 331 kW. The 911 Turbo was also built according to the biturbo concept and included the OBD II exhaust gas monitoring system as a world first. The 300 kW engine was based on the 3.6-l naturally aspirated engine, but was so comprehensively modified that it was regarded as an independent design [1, 4].

At the time of its world premiere in 1996, the drive of the new Boxster series represented a quantum leap in the development history of Porsche flat-six engines. For the first time, Porsche had integrated a water-cooled power unit with a 2.5-l displacement and output of 150 kW. Free from the limitations of the previous six-cylinder engine with air cooling, the engine developers integrated a cylinder head with two camshafts and four valves per combustion chamber in the new power unit [5]. One year later, the new 911 from the 996 series was launched, also with a water-cooled engine. With a displacement of 3.4 l, the engine was much shorter and flatter than its predecessor. It produced 221 kW and was much more lively than the previous naturally aspirated engine. In addition, the inlet camshaft could be adjusted, paving the way for the so-called VarioCam variable valve timing adjustment. Two years later, this system was extended to include a valve lift switchover and has carried the designation VarioCam Plus ever since. The 911 Turbo was also converted to water cooling and was equipped with a new 310 kW engine in 2000. Further development to increase the displacement and power output ran its course and flat engines with a displacement of 3.6 and 3.8 l and 261 kW emerged halfway through the 2000s [1].

In 2008, redesigned engines with direct fuel injection were installed in the 911 Carrera and 911 Carrera S models from the ground up – the 9A1 engine range had already won multiple international awards. They produced 254 and 283 kW respectively with the displacement unchanged. The engines installed in the Boxster and Cayman originated from the same family [6]. From about 2008 onwards, downsizing became a trend-setting requirement for engine engineers with the aim of increasing fuel efficiency. Based on solid know-how, Porsche developed new technology for the 911 from the 991 series, which was then launched in 2011: The flat engine in the 911 Carrera had an output of 257 kW and a displacement of 3.4 l instead of the previous 3.6 l. The 3.8 l displacement of the Carrera S remained unchanged. However, the power output was increased to 294 kW. Both models indicate that the 991 series was developed as a total package for the best fuel efficiency: With a power-to-weight ratio of 4.76 kg/kW, the new 911 Carrera S is the leader of the pack. In terms of NEDC fuel consumption, the 911 Carrera has raised the bar with 8.2 i/100 km (194 g CO_2/km) and the 911 Carrera S with 8.7 l/100 km (205 g CO_2/km) – each equipped with the Porsche Doppelkupplung transmission (PDK) [7].

The Boxster and Cayman compete in the two-seater roadster and coupé segment with the same characteristics. The 2.7-l engine produces 195 kW in the Boxster and 202 kW in the Cayman. With a PDK, both vehicles consume 7.7 l/100 km (180 g CO_2/km) in the NEDC. The Boxster S and Cayman S are equipped with a 3.4-l variant that produces 232 kW in the roadster and 239 kW in the sports coupé. Fitted with a PDK, both engines make do with 8.0 l/100 km (188 g CO_2/km) in the NEDC [1].

A uniform strategy has been pursued over the last 50 years, ❷: Enhancing the performance while at the same time reducing fuel consumption and increasing efficiency. And the trend is expected to continue. Of course, these objectives can only be achieved in synergy with the overall vehicle, for example:

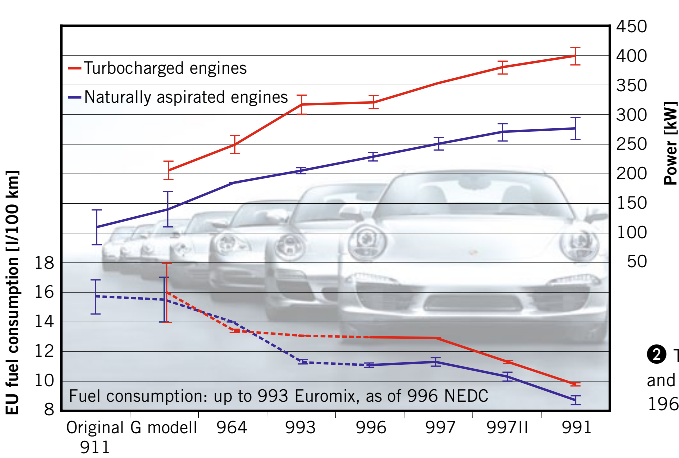
: overall design of engine, transmission and vehicle intelligent operating strategies
: reduction in the vehicle weight
: C_D value
: reduction in rolling resistances.

DEVELOPMENT HISTORY OF ENGINE DATA

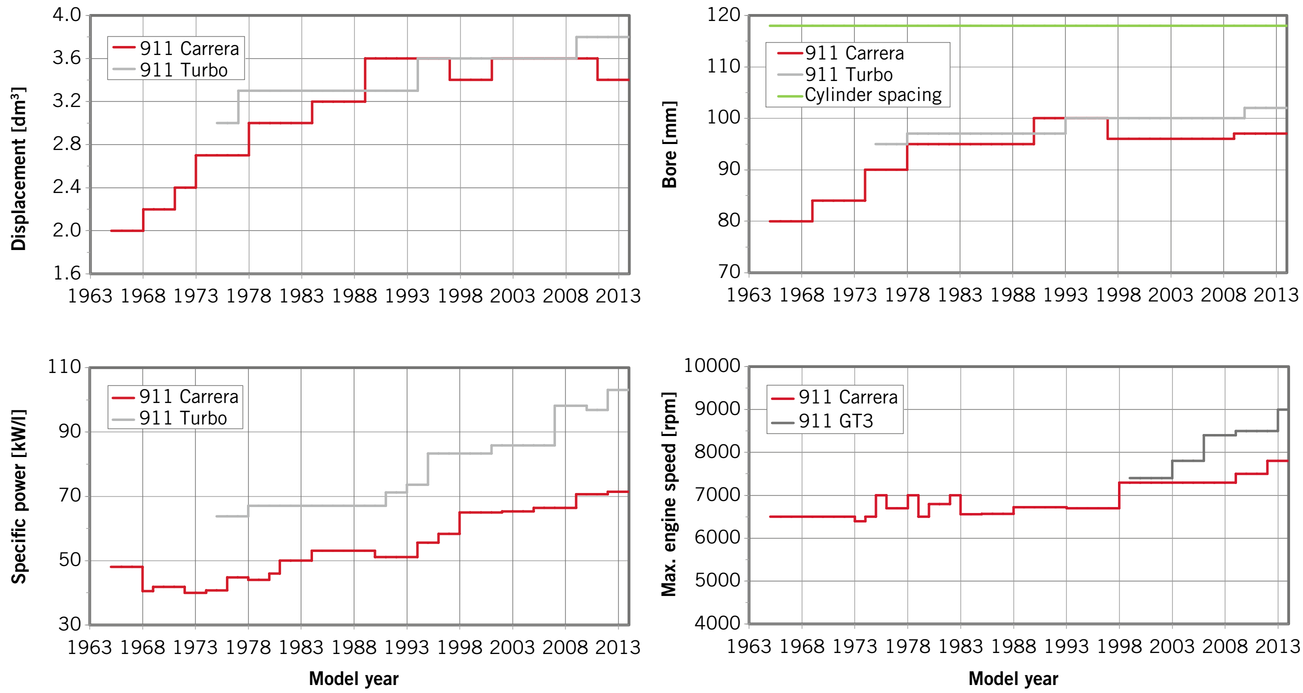
In the very early days, power enhancements were mainly achieved by increasing the displacement. Porsche always attached great importance to large bores and valve diameters as a prerequisite for a good gas cycle and high specific power. As a result, bores with a diameter of more than 90 mm were implemented at the start of the 1970s. At 118 mm, the cylinder spacing has remained unchanged since 1963, until today where the bore diameters have been increased to 102 mm, ❸.

In addition to the increase in displacement, the following measures were implemented to increase the specific power:

: gas cycle optimisation with simultaneous day-to-day drivability



❷ Trend in performance and fuel consumption since 1963



❸ Development history of engine data (examples)

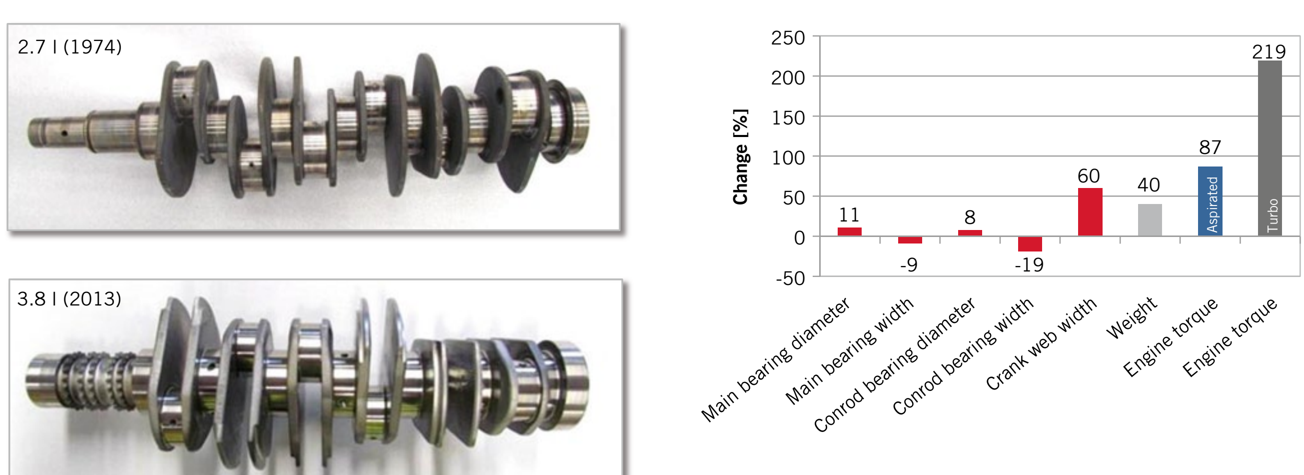
: introduction of modern combustion processes such as direct fuel injection introduced in 2008
: reduced friction
: increase in engine speed.

DEVELOPMENT HISTORY OF SPECIFIC COMPONENTS

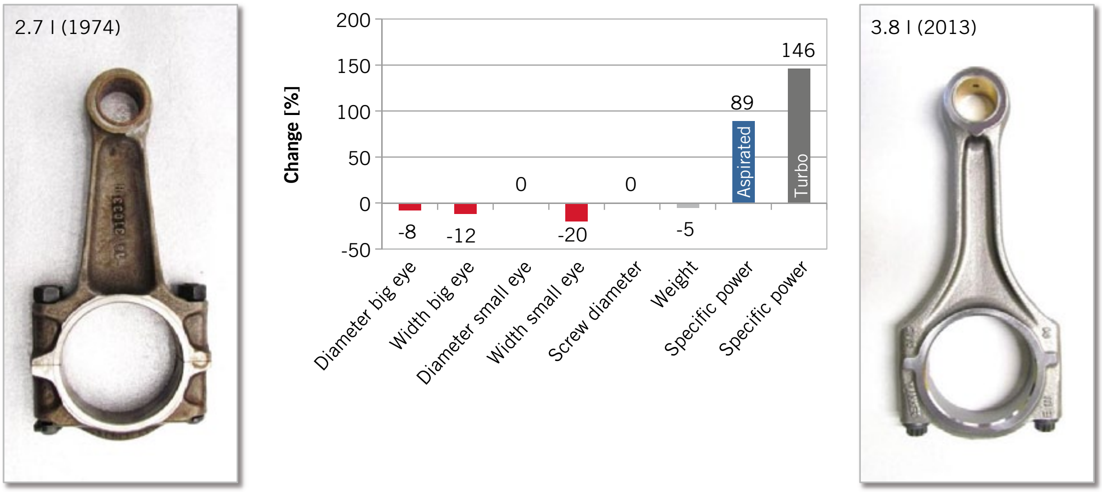
The development of Porsche flat-six engines is best demonstrated with reference to specific components. The specific crank drive is characteristic of a flat engine. From 1963 onwards, the crankshaft had seven bearings with an additional bearing on the belt drive side. Oil was supplied centrally to the main and connecting-rod bearings from a complex oil supply system. It had narrow side faces, comparatively wide main and connecting-rod bearing pins and a low weight.

The basic shape has remained unchanged partly due to the constant cylinder spacing, ❹. The transferred torques have increased significantly and require wider side faces, which results in lower bearing widths if the cylinder spacing is constant. An improvement in the oil supply, optimisation of the connecting rods, use of better bearing materials and detailed geometric optimisation ensure that the bearings function correctly. For example, in turbo engines from the current 911 model, which generate gas forces up to 82 kN, the connecting-rod bearings on the rod side have a sputter bearing design.

For the connecting rods and transfer of ever-increasing gas forces, the focus during the development phase is still placed on the following, especially in conjunction with the large bores used at Porsche:



❹ Comparison of crankshafts from 1974 and today



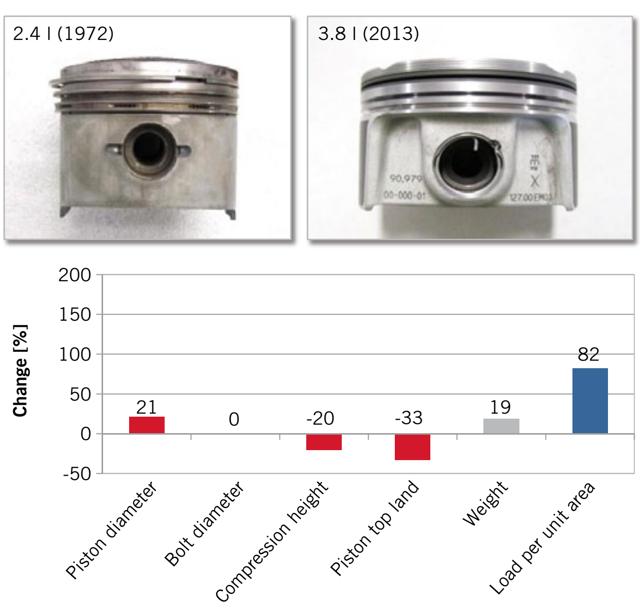
❺ Comparison of connecting rods from 1974 and today

: low moved masses
: revving stability
: long mechanical service life
: design of the connecting-rod bearings (low deformation at high speeds).

While the connecting rods were previously pinned and bolted into position, today only cracked connecting rods are used due to advantages such as strength and manufacturing precision.

Compared to before, ❺, it is apparent that the weight of the connecting rods has remained virtually the same, while the specific power of naturally aspirated engines has increased by 89 % and that of turbo engines as much as 146 %. Today, the only difference between the connecting rod on naturally aspirated engines and that of turbo engines are the dimensions (naturally aspirated engine: 140 mm, turbo: 138 mm) and piston pin diameter (naturally aspirated engine: 22 mm, turbo: 23 mm).

The piston, ❻, is the heart of the engine. The piston clearly demonstrates the conflict of objectives between the high specific power, large intake and outlet diameters required and large bores. The piston diameters have increased from 80 mm in 1963 to 102 mm today. The Porsche flat-six engines initially had cast pistons. With the exception of the 2.7-l piston (diameter 89 mm) in the Boxster and Cayman, only forged pistons (diameter 97 to 102 mm) are used today due to the demanding requirements.



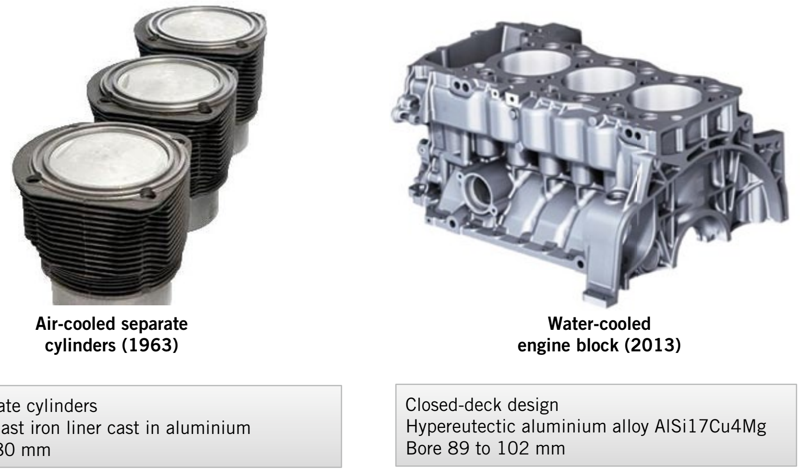
❻ Comparison of pistons from 1972 and today

The demands of today's gasoline engines require complex measures for reducing oil consumption and blow-by gases, such as ring fixing and defined leakage systems in the ring grooves, for example. Moreover, the minimisation of the piston junk height to reduce raw emissions conflicts with component strength and ever-increasing cylinder pressures. The reduction in the compression height and overall height of the piston is necessary to allow the moving mass to increase disproportionately to the specific power and allow high speeds.

For many years, the unique selling point of Porsche flat-six engines has been the air cooling system combined with the benefits of a low system weight. However, this resulted in disadvantages relating to the increasingly stringent statutory acoustic and exhaust emission requirements, as well as the potential for increasing the specific power. The original 911 had separate aluminium cylinder housings with embedded cast-iron bushings, ❼. The crankshaft was integrated in a separate housing. Today's cylinder crankcases demonstrate a high degree of integration. Other functions are integrated in addition to the main functions (crankshaft bearing assembly and cylinder lining):

: water cooling
: housing for timing drive mechanism
: oil circuit components
: mounting of various add-on parts.

Since 2008, the closed-deck design provides greater rigidity and allows high specific power. The assembly-friendly overall design, ⑦, includes features such



❼ Comparison of cylinders and track from 1963 and today

as a reduced number of sealing points and therefore meets the requirements of modern manufacturing plants and the latest quality standards.

The concept of the multi-part cylinder housing continues to be used, even among individual air-cooled aluminium cylinder heads, and has remained unchanged for a long time, ❽ and ❾. Features were:

: two-valve technology
: one overhead camshaft per side for intake and outlet valves
: chain drive with a hydraulic chain tensioner for each cylinder bank
: valve actuation via rocker arm
: focus on speed capability and endurance strength with high specific power.

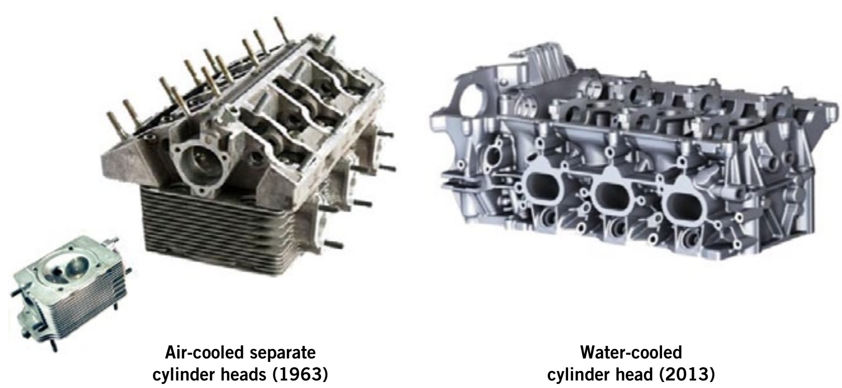
With ever-increasing power, exhaust gas emission and fuel consumption requirements, the limits of air cooling were reached in 1996 and Porsche decided to introduce water-cooled flat-six engines [5]. The main features of the cylinder head and valve drive concept, ⑧ and ⑨, were:

: water-cooled aluminium cylinder heads
: four-valve technology
: two overhead camshafts with bucket tappet drive with the prospect of variable valve timing and valve lifts.

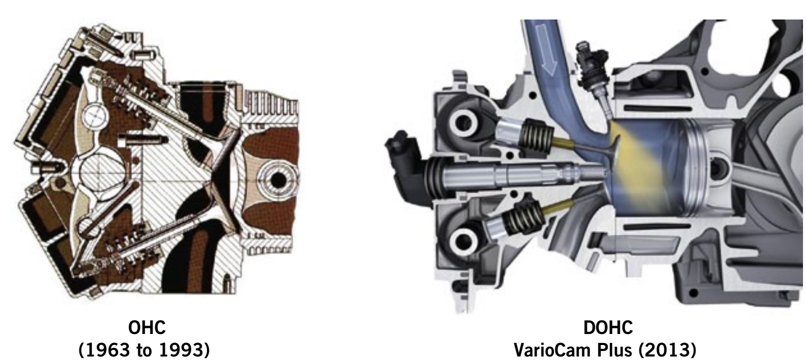
Since its introduction in 1996, the bucket drive has been developed to a current revving stability of 7800 rpm and also with a variable intake-valve lift. Today, special coatings and machining methods minimise the disadvantages of friction over the roller-type cam follower concept.

A two-stage camshaft control was used after 1996. A continuous camshaft control was used in the 911 Turbo following the introduction of the lift adjustment at the intake side in 2001. Porsche has used this concept in naturally aspirated engines since 2004 and continues to develop it today. The adjustment range of the camshaft control at the intake side is currently 50 °CA. The small intake-valve lift is 3.6 mm (5.6 mm with power kit) with a large valve lift of up to 11 mm on the 911 Carrera S (11.7 mm with power kit). In the VarioCam Plus system, approximately 80 % of the potential of a fully variable valve drive can be achieved at the same time as a high engine speed capability with an approximate workload of 20 %. Sliding valve levers are still used today in special engines such as the 911 GT3, for example. The intake-valve lift is 12 mm, but is not flexible.

High specific power requires a particularly good gas cycle. Aside from the cylinder head and valve drive, key components include the intake manifold and mixture formation of naturally aspirated and turbo engines. Purely from a design perspective, the flat-six engine offers a particularly good basis for an outstanding gas cycle because the cylinders at the intake and exhaust gas side have no influence on one another owing to the firing order and cylinder arrangement. The intake manifolds were consistently developed in combination with mixture formation systems to achieve multi-stage resonance induction for naturally aspirated engines and an expansion intake manifold on the 911 Turbo [8]. After the introduction of the new 9A1 construction kit in 2008, the VarioCam Plus system was combined with direct fuel injection.



❽ Comparison of cylinder head from 1963 and today



❾ Comparison of valve drive from 1963 and today

THE MODULAR PRINCIPLE

Performance and efficiency are necessary, but both must be guaranteed, even under economic constraints. All current flat-six engines therefore originate from the same family – the 9A1 construction kit introduced in 2008. While a general identical parts and technology strategy was already pursued before the introduction of the 9A1 construction kit with consideration for the specific technological requirements of individual derivatives, the 9A1 construction kit was implemented for the first time as an engine construction kit based consistently on a modular structure for use in derivatives of the Boxster, Cayman and Carrera. The requirements of highly supercharged units were also considered for the 911 Turbo. With modular engines, it was possible to achieve synergy effects in the development process and economies of scale as well as integrate economical variants in the construction kit, ❿.

In addition to a high proportion of identical parts such as

: connecting rods
: valve drive
: belt drive
: valve cover
: oil supply
: sensors and actuators
: connecting rod and crankshaft bearings
: high-load threaded joints (connecting rod, cylinder head, thrust block, etc.).

great importance was attached to the economical manufacture of components for variants. The cylinder crankcases and cylinder heads for all displacement variants, for example, are manufactured using a shared external mould. The variants are generated using specific sand cores and liners in the case of the crankcase. At the same time, these components are manufactured on joint production lines because they are processed in the same way. From an economic viewpoint, this approach is ideal for generating variants with consideration for the technical characteristics of individual derivatives. In the standard applications implemented today, the construction kit covers a displacement spread of 2.7 to 3.8 l, a power range extending from 195 to 412 kW and maximum engine speeds of 9000 rpm (in the 911 GT3) and is used in all current Porsche flat-six engines installed in production sports cars:

: Boxster (2.7 l, 195 kW) and Boxster S (3.4 l, 232 kW)
: Cayman (2.7 l, 202 kW) and Cayman S (3.4 l, 239 kW)
: 911 Carrera (3.4 l, 257 kW) and 911 Carrera S (3.8 l, 294 kW)
: 911 Carrera S with power kit (3.8 l, 316 kW)
: 911 GT3 (3.8 l, 349 kW)
: 911 Turbo (3.8 l, 390 kW) and 911 Turbo S (3.8 l, 412 kW).

FUTURE CHALLENGES

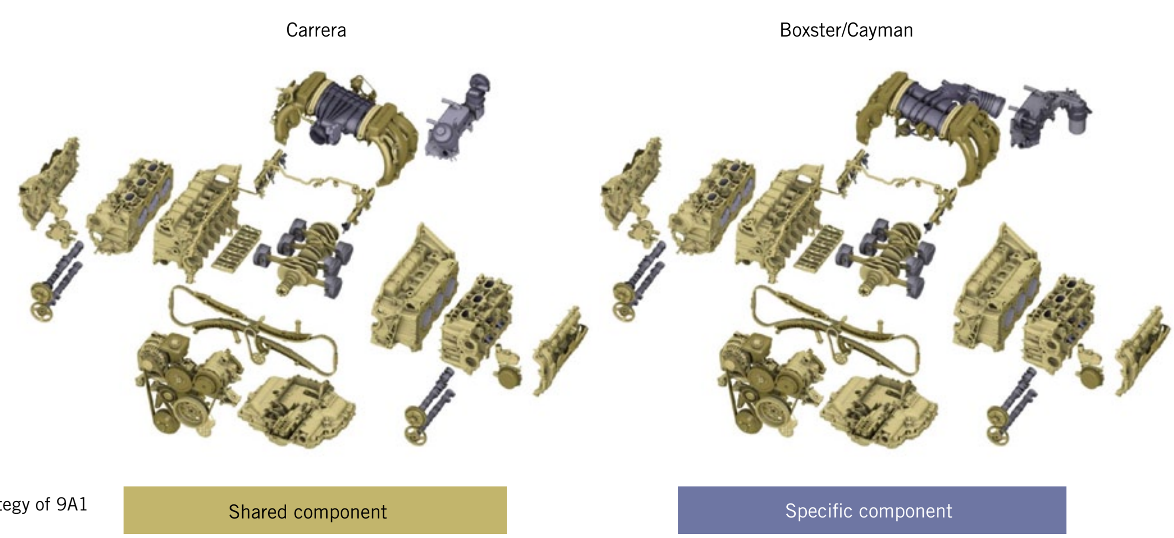
In addition to technical enhancements, an increase in performance twinned with a significant reduction in fuel consumption has always been a key focus in the development of Porsche flat-six engines. This will also represent an important challenge for new engine strategies in the future. In addition to compliance with future emissions legislation, this also includes maintaining typical brand characteristics, developing successful engine concepts for use in motor sport and implementing requirements arising from globalisation of the markets. Potential solutions may include:

: innovative lightweight concepts
: intelligent operating strategies in the overall engine, transmission and vehicle system
: optimisation of transmission ratio spread
: new injection systems and combustion processes
: displacement downsizing
: cylinder downsizing
: electrification.

These measures can be selectively integrated into the so-called Porsche Intelligent Performance concept.

SUMMARY

The development of Porsche flat-six engines 911 reveals that the performance has been continuously enhanced and fuel consumption reduced over the last 50 years, increasing overall efficiency. The last major overhaul of the Porsche flat-six engines proves that this engine concept can be successfully adapted to changing requirements and that the advantages afforded by concept can continue to be exploited. Continuing this success story is one of the challenges of the future, especially in the face of CO_2 targets. Construction kits have already been made available for this purpose.



❿ Identical part strategy of 9A1 construction kit [6]

The drive systems must be lightweight, efficient, powerful and have a high revving stability to qualify for installation in a Porsche 911. Achieving a fine balance between day-to-day usability and motor sport, exclusivity and social acceptance, innovation and tradition as well as emotion and function is essential. The flat-six engine is not a power unit of yesterday, but forms the basis for the efficient sports engine of tomorrow.

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