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Der Antrieb des Mini Cooper S

# The Mini Cooper S Powertrain

Following the Mini One and the Mini Cooper, the top-of-the-range model with a power output of 120 kW is now being launched. In order to meet the high demands in terms of power, torque and engine sound as well as everyday practicality, the 1.6 litre used in the smaller models has been extensively modified.

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## 1 Introduction

The excellent performance and outstanding handling of the Mini have made its name synonymous with exceptionally pleasurable driving. The new Mini is set to continue this tradition of success, which has included many sporting highlights in the past. With their agility, sporty chic and unique handling characteristics, the Mini One and the Mini Cooper opened up a further chapter in this story. And now the range has been completed by the Mini Cooper S – the model with the most powerful engine. This “driving machine” combines an engine of outstanding performance and a sporty six-speed gearbox in perfect unity. The Mini Cooper S thus has everything it takes to set new standards for enjoyable driving in its class. Development of its powertrain involved a special degree of motivation and was a major challenge because of the car’s compact dimensions.

## 2 Development Goals

In view of the demands made on the Mini Cooper S, priority was given to the following powertrain development goals:

- maximum power output 120 kW, maximum torque 210 Nm
- ample torque even at low engine speeds
- lively engine response
- low fuel consumption combined with high performance
- compliance with EU4 and LEV emission limits
- smooth, low-vibration power unit
- sporty engine sound
- quality and reliability to BMW standards
- compact construction.

## 3 Drive Concept

Mini is an autonomous brand among the BMW Group’s products. In line with Mini traditions, a front-wheel drive layout was chosen, as is customary in this class. The four-cylinder engine is installed transversely and is on the right when looking towards the front of the car. The six-speed gearbox specially developed for the Mini is on the left and sets new standards in this class of vehicle.

As with its predecessor, the new Mini’s engine compartment is extremely compact. The task for the engineers was to develop a top-of-the-range engine offering a significant increase in power over the Mini Cooper with its already attractive 85 kW engine and to squeeze it into this tightly packed engine compartment. In addition, there was to be no departure from the modular concept of the Mini. Given these constraints, the best technical solution was a supercharged power unit.

Selecting the method of supercharging involved thorough preliminary studies and calculations on all important engine functions. The decisive factor which led to the choice of a supercharger to give the Mini Cooper S the desired characteristics was the virtually lag-free response of this mechanical device. Fundamental analysis showed that mechanical supercharging offered significant drive-off advantages compared with a turbocharger of the standard currently available for spark-ignition engines up to a cubic capacity of about 1.6 litres.

Another advantage of a mechanically driven supercharger is more rapid catalytic converter light-off, since it eliminates the mass of the turbine casing with its associated heat capacity, and the converters therefore reach their light-off temperatures more quickly. It also significantly reduces the amount of heat to be dissipated from the engine compartment. Moreover, the fact that all the additional components of a mechanical supercharging system are concentrated on the intake side of the engine offers significant advantages in terms of packaging and significantly reduces the length of the air intake path.

## 4 Design Configuration of the Engine

### 4.1 Design of the Basic Engine

The basic engine in the Cooper S, **Title Figure**, is based on the 1.6 litre four-cylinder unit familiar from the Mini One and the Mini Cooper. This engine is made by TRITEC, a BMW Group and DaimlerChrysler joint venture. Owing to the new version's high specific power output, however, a number of modifications were required, and these will be discussed later. The technical data for the engine in the Mini Cooper S are shown in Table 1.

#### 4.1.1 Combustion Chamber, Pistons

A bore/stroke ratio of 77/85.8 mm has been retained, in other words a long-stroke configuration. The pistons are made from the high-temperature alloy AL 142 by the Mahle company. The piston groove for the compression ring is anodised and the height of the piston's top land is only 4 mm, a very low figure for a supercharged engine.

To avoid piston overheating even in continuous full-load operation, the engine has an oil cooling system for the pistons. The technology for this was adopted from BMW engines. Essentially, it consists of nozzles that spray the pistons with oil from below, thereby cooling them. These nozzles open at an oil pump pressure of about 2.5 bar and have a maximum oil delivery rate of 2.2 l/min. Oil cooling reduces the temperature of the pistons in the zone around the centre of the crown by as much as 50 degrees to a maximum of 250 degrees.

#### 4.1.2 Reciprocating Elements

Because of the significantly higher peak combustion pressures compared with the basic naturally aspirated engine, considerable modifications have had to be made to the crank mechanism as well. Whereas the basic version is fitted with a cast crankshaft, a drop-forged steel crankshaft is used on the Cooper S. There is no need to harden the crankpins and main bearing journals, but three-layer bearings are used to cope with the higher bearing forces involved. The crankshaft is supported at five points and has 8 counterweights, which provide 80 % balancing. This configuration minimises free vibration and bearing loads.

The connecting rods have also been fundamentally modified. The basic engine is fitted with sintered rods, but the Mini Cooper S uses a forged version with computer optimised geometry. As with the basic sintered version, these rods are "cracked".

#### 4.1.3 Oil Pump

The oil pump has been modified to meet the higher volumetric flow requirements imposed by the oil spray nozzles. It is a "gerotor" gear-type pump driven directly from the crankshaft and is an integral part of the timing drive cover. The only modification required was to optimise the flow characteristics of the control lips at the inlet and outlet sides of the pump. This yielded an increase of about 15 % in the flow rate. The pressure-regulating system has also been reconfigured to ensure that the required supply pressure of at least 3 bar is available even at critical engine speeds. This made it possible to avoid the alternative of widening the gearwheels in the pump, which is associated with an increase in friction.

#### 4.1.4 Cylinder Head and Valve Gear

The cylinder head has also been redesigned to increase power output. The main emphasis here was on adapting the passages to the higher gas flow. In particular, the maximum flow rate on the exhaust side has been increased by 30 % by optimising the geometry of both the passages and the valves. It also involved reducing the valve stem diameter below the guide to 5 mm. The valve timing for the 85-kW engine proved to be ideal for the supercharged unit as well. The spread is 111 degrees of crankshaft rotation on the inlet side and 109 degrees on the exhaust side.

The geometry of the valve gear has to a large extent been taken over from the basic version. It is a compact valve timing system with an overhead camshaft, aluminium roller rockers and integral hydraulic valve lash adjusters. There are three rockers per cylinder: two for the inlet valves and a tandem rocker for actuating the exhaust valves. Since the exhaust valves for the supercharged engine have to open against a higher cylinder pressure, the forces in the valve gear increase accordingly. In addition, the engine's governed speed limit has been raised to 6,950 rpm. The tandem rockers for the exhaust valves have therefore been modified to accommodate the higher loads with additional material and tighter tolerances between the roller shaft and the rocker.

As a departure from the basic version, the exhaust valves are manufactured from Inconel to take account of the significantly higher temperatures involved.

### 4.2 Design of the Supercharging System

#### 4.2.1. Supercharger and Drive

A helical-action supercharger has been used for reasons of efficiency and acoustics. This and the other auxiliaries are driven from the crankshaft by a 6-groove V-belt, the supercharger being located in front of the engine. The transmission ratio is 2.06. At an engine cut-off speed of 6,950 rpm, the supercharger thus runs at 14,317 rpm.

The basic engine for the Mini One and the Mini Cooper is fitted with a conventional torsional vibration damper at the front end of the crankshaft. Calculations and measurements showed that the addition of the supercharger with its relatively high moment of inertia was resulting in excessive torsional vibration at about 1600 rpm. This solution was unacceptable both acoustically and in terms of component strength.

The torsional vibration damper used on the Mini Cooper S engine therefore has the belt pulley additionally isolated elastically from the secondary mass, with belt drive vibration damping. Vibration amplitudes are significantly reduced by the isolated belt pulley. However, the decisive factor is that the most marked resonance is shifted into a zone below idle speed and is therefore outside the engine's operating range, **Figure 1**.

Another special feature that should be mentioned is that the water pump is driven via a coupling and reduction gears from the rear end of the supercharger. The reduction gears are integrated into the supercharger housing. This is filled with a small quantity of oil by the manufacturer and requires no further lubrication for its entire service life. This arrangement was made necessary by the lack of space in the belt drive for a direct drive to the water pump.

**Figure 2** shows the mapped operating characteristic for the supercharger, with the pressure ratio plotted against volumetric flow. Also shown are the engine speed and the speed and efficiency of the supercharger. The thick red line indicates the absorption limit of the engine and shows that it is designed for a high specific output. The thick black line, on the other hand, indicates the pressure downstream from the charge-air intercooler. The difference between the lines represents the pressure drop in the intercooler.

#### 4.2.2 Charge-Air Path

For reasons of space, the intercooler is arranged above the engine. A prominent air scoop towards the front of the engine hood feeds air to the intercooler as the car moves forward. Another particularly decisive factor in the excellent efficiency of the intercooler is the ease with which the air can flow out of the engine compartment underneath the intercooler. The airflow has been optimised by extensive calculations and tests, resulting in good intercooling rates at all the relevant operating points.

The intercooler is attached to the intake system by semi-flexible retention plates. This ensures that it is secured rigidly to the engine in the principal directions of vibration. On the other hand, however, this construction allows relative motion in the longitudinal direction of the intercooler in response to temperature changes, thus minimising stresses. The retention plates are designed in such a way that excessive resonance does not occur in any operating range, thus meeting all the acoustic and component strength requirements. Tolerances and relative movement due to temperature changes are also allowed for by bellows at the intercooler inlet and outlet. The bellows are secured by two-piece diecast aluminium clips.

The throttle is arranged upstream of the supercharger, whereas the bypass valve is positioned downstream for reasons of space. The charge air released is re-introduced between the throttle and the supercharger, **Figure 3** and **Figure 4**.

The electrically operated throttle butterfly is controlled by the electronic engine management system and is identical in construction to those used on other BMW engines, both in terms of the underlying concept and many of its component parts. The bypass valve, on the other hand, is controlled by the vacuum in the intake manifold. The intake pipes are very short, with a length of about 110 mm (from cylinder head to manifold), with a view to achieving advantages for the charge cycle in the upper engine-speed range. Aluminium was chosen as the material for the intake system. Its geometry has been mathematically optimised to ensure uniform inflow to the cylinders and prevent the fuel/air mixture from flowing back up the very short intake pipes and into adjacent pipes via the manifold.

#### 4.2.3 Engine Management

The Siemens engine management system is based on a modern torque-based architecture.

The engine load is detected by a p-n control system, eliminating the need for an air mass meter. Instead, a pressure/temperature sensor arranged in the manifold supplies the electronic system with the information required for engine control.

Engine load is controlled by a "drive-by-wire" system. This also permits additional functions such as integrated idle-speed control and cruise control and is a prerequisite for the operation of suspension control systems, e.g. traction and dynamic stability control.

## 5 Design Configuration of the Gearbox

### 5.1 Gearbox Concept

In line with the character of the Mini Cooper S, the manufacturer has chosen to fit a six-speed sports gearbox. The term sports gearbox indicates relatively close spacing between the gears and hence maintenance of the flow of power between them, Table 1.

The front-mounted transverse configuration was a major design challenge when it came to the length of the engine/gearbox unit. In designing the Mini, maximum crash safety and therefore optimum configuration of the longitudinal members in the engine compartment and front body section were priorities. This requirement imposed an additional limit on the permitted length of the engine/gearbox assembly. Because the length of the engine is largely fixed, depending on the spacing between the cylinders, the length restriction on the powertrain as a whole determines the length available for the gearbox.

There was therefore no room in the Mini's engine compartment for a conventional two-shaft six-speed gearbox with all the gears arranged one behind the other. Working with the Getrag company, BMW therefore developed a compact three-shaft gearbox with one input and two output shafts, in which certain gearwheels are used twice to permit a considerably shorter gearbox, **Figure 5** and **Figure 6**.

To avoid unpleasant rattle from the gearbox, a dual-mass flywheel is located between it and the engine. This is a spring-mass system and operates in the super-critical range, thus isolating torsional crankshaft vibration from the gearbox.

### 5.2 Configuration of the Gears/Gearwheel Layout

As already mentioned, the gearbox has been constructed with two separate output shafts for reasons of space:

- output shaft AB1 with free gears for gears 1-2-5-6
- output shaft AB2 with free gears for gears 3-4-R.

The special feature of this concept is that gears 3 to 6 are each driven in pairs by a single fixed gear, **Figure 7**.

- The fixed wheel Z3/5 on the input shaft meshes simultaneously with free gears Z3 and Z5; depending on the gear selected, fixed gear Z3/5 transmits the torque in gears 3 and 5.
- The fixed gear Z4/6 on the input shaft meshes simultaneously with free gears Z4 and Z6; depending on the gear selected, fixed gear Z4/6 transmits the torque in gears 4 and 6.

The two output pinions/constants RA1 and RA2 are simultaneously in mesh with the output gear on the differential casing.

The gearbox thus has two axle ratios, which define the overall ratio of the gearbox depending on the gear selected. **Figure 8** shows a demonstration model of the gearbox.

## 6 Engine Functions

### 6.1 Power and Torque

Whereas the engines for the Mini One and the Mini Cooper are designed for power outputs of 66 and 85 kW respectively, the ambitious goal for the sporty Mini Cooper S was an output of 120 kW and a maximum torque of 210 Nm. All relevant aspects of the basic 1.6-litre engine used in the Mini One and in the Mini Cooper were therefore designed from the outset for the high specific power output of 75 kW/litre and torque of 131 Nm/litre. Using the supercharger, it has been possible to achieve a very smooth, sporty torque curve. The short intake pipes also contribute to its character and enable the high specific power output to be achieved, **Figure 9**.

In order to ensure an optimum configuration in terms of power and fuel consumption at the prevailing boost pressures of up to 1.9 bar, a compression ratio of 8.3 : 1 was chosen. The best shape for the combustion chamber with regard to both efficiency and knock resistance was obtained with a piston containing a lenticular combustion-chamber bowl measuring 1.6 $cm^3$.

With the aid of knock control, this makes it possible to use 91 to 98 RON fuels throughout the world. However, the basic design has been optimised for RON 98.

As a result of the measures described above, the Cooper S engine compares extremely well with other 1.6-litre engines in terms of its engine characteristics, **Figure 10**. Compared with other supercharged four-cylinder engines, its specific data put it among the leaders.

The engine power characteristic results in excellent performance figures. The car can accelerate from 0-100 km/h in 7.4 seconds. Acceleration from 80 to 120 km/h takes 6.7 seconds in fourth gear and 8.7 seconds in fifth gear. Top speed is 218 km/h.

### 6.2 Fuel Consumption

Despite this high performance, the Mini Cooper S also achieves good fuel consumption figures: 8.4l/100 km in the EU cycle, **Figure 11**. The low-friction basic engine, its long-stroke configuration and the optimised combustion chamber shape are the technical factors that compensate for the disadvantages inherent in the supercharged principle.

### 6.3 Emissions

The pipes for the exhaust manifold were designed to minimise its heat capacity and ensure that the catalytic converters heat up quickly. They are of 4-in-1 construction. A funnel designed for optimum flow is arranged downstream of the isolating element that is usual with transverse engines. This ensures a uniform flow of exhaust gas to the first oxygen sensor and at the inlet to the front converter, the one closer to the engine. The main catalytic converter, on the other hand, is designed for underfloor installation, **Figure 12**.

The front catalyst has a metal monolith with a volume of 0.3 l and 300 cells per square inch. The volume of the main catalyst is 1.26 l. It is based on a 400-cell ceramic monolith with a wall thickness of 6.5 mil.

Effective combustion chamber design and the short piston top land help to keep emissions of untreated hydrocarbons to a very low level. At a load point of n = 2000 and a mean effective pressure of 2 bar, they amount to just 2.9 g/kWh.

This makes it possible to achieve a very efficient emissions concept. The Mini Cooper S already complies with the strict limits of future EU4 legislation and is also certified for the American market in accordance with LEV regulations. Systematic implementation of the concept has made it possible to dispense with expensive additional systems such as EGR and SLS. All currently valid on-board diagnosis requirements have been met.

### 6.4 Engine Sound

A sound that matches the car's character helps to enhance the typically enjoyable experience of driving the Cooper S. Special modifications to the intake and exhaust systems ensure that this top-of-the-range model stands out from the Mini One and the Mini Cooper not only by virtue of its appearance and performance but also acoustically.

As far as the flange joint downstream from the manifold/converter, it was possible to use the same components. After that, the Cooper S exhaust system's design differs significantly. Apart from the higher gas flow and modified sound requirements, it was also necessary to take account of the design requirement for a twin tailpipe at the centre of the car and the need to accommodate the starter battery at the rear. Placing a central silencer on the right-hand side at the rear has eliminated the need for a front silencer on the Cooper S, **Figure 13**.

The relative volumes of the central and rear silencers and the choice of pipe length and cross-section combined with their matching internal structure ensure that the low-frequency components of the sound at the outlet determine the acoustic background both inside and outside the car, **Figure 14**.

An acoustically transparent load-area cover ensures that the sporty sound of the exhaust system can be heard as directly and authentically as possible. In the middle and upper engine-speed ranges, the design of the intake silencer and its arrangement upstream of the equipment bulkhead ensure that the driver obtains acoustic feedback from the supercharger according to engine load.

To keep within the 74 dB(A) external noise limit for cars despite these acoustic modifications, extensive sound cleaning had to be applied to all sources of noise that were not essential to enhance the acoustic experience.

In particular, externally directed noise from the supercharger and the engine, surface noise from the exhaust system and high-frequency components at the tailpipes have been reduced to a minimum.

## 7 Summary

Following the successful launch in Spring 2001 of the new Mini One and Mini Cooper with 1.6-l naturally aspirated engines developing 66 and 85 kW respectively, the top end of the range is now rounded off by the Mini Cooper S with this agile, supercharged engine. With an output of 120 kW and the high specific power output of 75 kW/l, this engine is among the leaders in its class.

Thanks to the systematic design for low levels of untreated emissions, it complies with the strict requirements of EU 4 and LEV without complex exhaust treatment technology.

Sophisticated, load-dependent sound engineering on the exhaust and supercharging systems makes driving the car a pleasure to the ears. The close-ratio 6-speed gearbox matches the sporty powertrain concept perfectly. ■