Turbochargers in the workshop
Technology, variants, troubleshooting

Mario Köhler
Krauthand Medien GmbH

powered by BorgWarner
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by
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Foreword

Turbocharging internal combustion engines in cars using one or more turbochargers has become considerably more important over the past few years. This is due to the tendency to design smaller, more powerful engines while also reducing fuel consumption and exhaust emissions. This presents designers and engineers with a constant source of challenges. In the long run motor vehicle servicing experts have to be able to keep up with the increasingly complex technical steps being made and understand the overall turbocharger system.

Exhaust turbochargers are designed to last for the entire service life of an engine under normal circumstances and when the peripheral equipment has been maintained properly. In practice, this is by no means the case. The spotlight generally only falls on the turbocharger when a customer brings their car to a workshop and reports loss of power, noise, smoke, and similar issues. This is the point where the skilled motor vehicle mechatronics technician is consulted.

This specialist brochure, “Turbochargers in the workshop – Technology, variants, troubleshooting”, from the KRAFTHAND Practical Know-how series, provides a clear and detailed overview of the subject. It serves as a practical guide for everyday workshop routines and is aimed at trainees and vehicle diagnostics experts alike.

In particular, I would like to thank BorgWarner Aftermarket Europe GmbH, Kirchheimboland, for their support with the compilation of this publication.
I would also like to thank both BorgWarner and Georg Blenk of Krafthand Medien GmbH for providing additional information. This specialist brochure would not have been possible without you.

I hope you enjoy reading this publication and that you learn a lot from it!

Wittighausen, June 2017

Mario Köhler
1. A brief history

The history of the turbocharger is as old as the internal combustion engine itself. Efforts to achieve more power with less fuel consumption date all the way back to the very start of engine design. Back in the day, Gottlieb Daimler worked on the supercharging of internal combustion engines. In those days cars ran on gasoline and gas. Daimler patented his solution in 1885. However, the procedure was not particularly effective. He used the hollow spaces in the crankcase and compressed the air using the underside of the piston (comparable with the precompression of a two-stroke engine). However, he dismissed this idea after a few attempts as the success he had been hoping for failed to materialize. The Daimler corporation did not return to the concept of turbocharging until more than 30 years later.

Rudolf Diesel achieved similar success when he tested engines on the basis of the same principle as Daimler, back in 1896. He found, to his dismay, that the effective power did in fact increase slightly but that the efficiency was massively impaired. Diesel was unable to explain the inefficiency impairment in this regard and felt that precompression (supercharging) per se was harmful. The subject was not pursued for a time following Rudolf Diesel’s negative appraisal.

In 1905, Alfred J. Büchi developed the principle of the exhaust compressor – a device now termed the turbocharger. Büchi was able to achieve a performance increase of around 40 percent. The turbocharger has since been recognized officially as a performance-enhancing component in the development of internal combustion engines.

In 1938, Swiss Machine Works Saurer developed a turbocharged engine for trucks. However, the first truck engine in series production did not appear until much later, namely in a Scania vehicle launched in 1961.

The Garrett Corporation, founded by J. C. Cliff Garrett in 1936, developed the first charge air cooler for the American B-17 bomber. This was installed between a General Electric turbocharger and a Pratt and Whitney engine. Numerous aircraft engines were fitted with turbochargers during the Second World War.

1952 heralded the start of development of turbochargers at Kühnle, Kopp & Kausch AG (“3K” for short), a company located in the Palatinate region in South-Western Germany. In parallel, US company Schwitzer fitted the first turbocharger to a Cummins Diesel Racer. 1954 saw the first use of a Schwitzer turbocharger in series production of Caterpillars.

In 1960, Kühnle, Kopp & Kausch opened a new turbocharger production plant in Kirchheimbolanden which is now one of 10 turbocharger production sites and one of 62 BorgWarner sites worldwide.
The first turbocharger (supplied by Garrett) was implemented more or less successfully in a series-produced car (an Oldsmobile Turbo Jetfire) in 1962. This resulted in numerous engine failures and a very narrow power delivery band. Had the era of turbocharging ground to a halt before it really began? Absolutely not. In motorsports in the 1970s, an unprecedented performance increase was achieved in Formula 1 engines thanks to turbochargers. This heralded a major breakthrough for the turbocharger. Production models such as the Mercedes 300 TD (1978) or Golf 1.6 TD (1981) followed.

In 1997, BorgWarner Automotive acquired a majority shareholding in Kühnle, Kopp & Kausch AG. This was followed in 1998 by BorgWarner’s takeover of Schwitzer and its integration in BorgWarner Turbo Systems together with 3K-Warner.

Current turbocharger technologies, indicated by designations such as TDI, TFSI, TSI, TDCI, and CDI, are now common sights in workshops. Various underlying technical approaches exist. The latest technologies include electrical compressors such as BorgWarner’s eBooster (or e-Turbo in commercial vehicle applications) or Valeo’s e-Charger.
2. A quick look: The internal combustion engine

A turbocharger only works correctly when the internal combustion engine itself is operating flawlessly. For this reason, we will provide here a few relevant details about internal combustion engines to facilitate your overall understanding.

The compression ratio is the ratio of displacement (total volume) to the combustion chamber (the residual volume after compression). The displacement is measured when the piston of a cylinder is located between bottom dead center (BDC) and the upper edge of the cylinder liner. Automotive experts measure the combustion chamber from the piston crown to the spark plug, i.e. the chamber filled with combustion gas that is adjacent to the piston during ignition. In this case, the piston is at top dead center (TDC).

The compression ratio is dependent on the fuel selected (knock resistance) and the nature of the internal combustion engine (naturally aspirated engine or turbocharged engine). For naturally aspirated engines (gasoline), compression ratios of 10:1 to 11:1 (and, in part, to 14:1) are tried and tested. The compression ratio is higher for diesel engines, around 18:1 to 23:1, so that self-ignition is possible.

This is not quite the case with turbocharged engines. The combustion chamber is virtually “pumped full” of air: in other words, the basic compression in a gasoline engine is between 10:1 and 8:1 as the air is virtually already precompressed. Turbocharged diesel engines are mostly compressed to a lower level: these values are between around 14:1 and 18:1. A high compression ratio has a positive effect on efficiency, performance, and fuel consumption.

In the case of gasoline engines, the upper limit for the compression ratio is exceeded when the engine starts to “knock”. This means that the air-fuel mixture ignites spontaneously due to the high pressure and high temperature – this happens just before TDC and the spark plugs provide the actual ignition sparks.

2.1 Power formula and contexts

The power output of an internal combustion engine is calculated from the total displacement, mean working pressure and speed. The formula for this is $P_1 = V_h \times p_1 \times n / 1,200$ (four-stroke engine). Calculated power output is higher if these parameters are increased.

The trend for the engines of today is to use less displacement ($V_h$). General downsizing achieves effects such as reduced internal friction losses and less external thermal radiation. The smaller displacement is compensated for by a higher working pressure ($p_1$) – in other words, turbocharging.
A quick look: The internal combustion engine

The speed (n) in internal combustion engines can be increased by means of the following parameters:
- friction reduction by means of better materials (pistons, piston coating, cylinder surfaces, piston rings),
- reduced contact pressure,
- a lighter flywheel,
- an improved valve drive,
- an rpm limiter, by increasing the value using appropriate software.

The displacement can be enlarged by means of a larger bore, i.e. larger pistons, and a longer stroke as well as an amended crankshaft (or a combination of the two, if so permitted by the space available and the engine block). This is in keeping with the motto “there is nothing to replace displacement, except more displacement”.

The mean working pressure (p₁), which in practice has the greatest part to play, is influenced and/or increased by means of a sufficient cylinder charge and high compression. To find out whether the cylinder charge can be further improved, the automotive expert looks at the volumetric efficiency of the engine.

Volumetric efficiency = aspirated fresh gas volume/cylinder volume

Advantages offered by turbochargers

Compared with equally powerful naturally aspirated engines, turbocharged engines use less fuel. The space required by a turbocharged engine is smaller than by a naturally aspirated engine of equal power.

The altitude behavior (e.g. power delivery in alpine regions) of the turbo engine is considerably better. A naturally aspirated engine loses considerable amounts of power as a result of the decreasing air pressure at altitude. In turbo engines, the turbine power increases as there is a fairly large pressure drop between the almost constant pressure before the turbine and the lower ambient pressure. The lower air density at the compressor inlet is thus largely compensated. The engine loses hardly any power. Compared with a naturally aspirated engine, the turbo engine is also quieter as the turbine and compressor wheel act as silencers.

Disadvantages of turbochargers

Engine blocks, crank mechanisms and pistons have to withstand higher loads in the case of turbocharged engines. The operating temperatures are higher (up to 1,050°C). Older turbocharger applications suffered of poor response in the lower rpm range (turbo lag). The oil supply is more expensive. Contaminants in the exhaust system reduce turbocharger service life (source: Struck Turbotechnik, Cologne).

Tip

Turbo engines are warmed up and then left to cool down slowly – particularly after a spirited motorway run – without switching off the engine immediately. Later-generation vehicles are fitted with start-stop systems. The system can be deactivated manually. This is frequently provided by the manufacturer at system level and at corresponding temperatures.

Info

Essentially, any engine with a regulated turbocharger has the advantage of being able to compensate for the external conditions to an extent by means of readjustment.

Info

The volumetric efficiency is the ratio of the available fresh gas volume in the cylinder to the actual volume. A practical example: A one-cylinder, four-stroke naturally aspirated engine with a volume of 500 cm³ has a volumetric efficiency of max. 70 percent. This means that of 500 cm³, only 350 cm³ is filled with fresh gas.

The cylinder charge can be improved by means of the following parameters:
- the design of the intake manifold,
- the shape of the cylinder head,
- amended valve cross-sections and valve lifts,
- amended timings,
- amended ignition timing,
- the design of the combustion chamber
- and the mixture control and turbocharging.

Info

The volumetric efficiency in series-produced engines stands at between 60 and 90 percent. This figure is between 140 and 270 percent for turbocharged engines!
3. Turbochargers: Components, operating principle

3.1 The core assembly or CHRA (center housing rotating assembly)

Turbochargers essentially have an exhaust side and a fresh air side. The main component, known as the core assembly, comprises the bearing housing, the bearing system itself and the rotor shaft on which the turbine wheel and compressor wheel are located. The compressor wheel is located on the fresh air side, while the turbine wheel is located on the exhaust side.

The turbocharger operating principle

When operating, hot exhaust gases are emitted from the engine and fed to the turbocharger via the exhaust manifold. Depending on the exhaust gas volume, the exhaust gases generate a rotary movement at the turbine wheel and this is transmitted via a shaft 1:1 to the compressor wheel. The compressor draws in fresh air via the intake duct, compresses it and passes the air via the intake duct into the engine’s cylinder at the resulting overpressure.
Turbochargers: Components, operating principle

Constant pressure turbocharging

In the case of what is known as constant pressure turbocharging, the total exhaust gas volume of all cylinders is collected in the exhaust manifold and fed centrally to the turbocharger’s turbine.

Pulse turbocharging

In the case of pulse turbocharging, partial exhaust volumes for each cylinder are fed to the turbocharger via a shared “nozzle”. This results in a faster, more spontaneous response. Pulse turbocharging has one considerable advantage in the case of lower engine speeds as the dynamic energy from the exhaust pulses can partially compensate for the low mass airflow.

There is a corresponding adverse effect on engines with a turbocharger designed with emphasis on pulse turbocharging in terms of rated power.

Combination

In practice, a combination of constant pressure turbocharging and pulse turbocharging is selected for reasons of space. The choice of procedure is also dependent on the number of cylinders, the design of the engine, the desired power and preferred engine characteristics. Three factors are relevant to drive the turbine: the exhaust gas pressure, the exhaust gas temperature and what is known as the flow – the mass airflow.

A quick look:
Supercharging by means of a compressor

Another option for increasing the performance of an internal combustion engine is to use purely mechanical supercharging by means of a compressor. In this system a compressor wheel in the intake duct is driven by the engine itself. However, the performance increase achieved in this case is partly reduced due to the increased drive power of the compressor (up to 15 percent). Compared with turbocharged engines, fuel consumption is slightly higher.

Another compressor variant, but using a different compressor concept, is what is known as the G-Lader, which was used at Volkswagen in vehicles such as the Golf II and III, Polo II, Passat G60 Syncro and Corrado. The air is compressed using what is known as the scroll procedure. In this regard, two displacer plates equipped with spirals move radially in relation to one another. The G-Lader is also driven mechanically by the engine by means of a belt.

3.2 The rotor shaft bearing

In the case of the turbochargers of today that are installed in series production, the rotor shafts achieve speeds of over 300,000 revolutions per minute (example: the extremely small charger in the Smart CDI). The rotor shaft bearings have to be designed accordingly.
We differentiate between two bearings, the radial bearing (absorbs the force radially) and the axial bearing (absorbs the force in the longitudinal direction of the shaft). The radial bearing can be designed as a one or two-bush plain bearing and runs in a wear-free manner on a film of oil.

In the case of the one-bush bearing, the bush is pressed securely into the bearing housing and only the shaft rotates. The advantage of this is a more compact design and less distance between bearings.

This is not the case with the two-bush bearing. This is designed so that there is a brass radial bearing bush rotating at half the speed of the shaft between the stationary bearing housing and the rotating shaft. Hence there can be no friction between the bearing and the rotor. The external film of oil is used for damping and ensures that the rotor shaft is stable.

Bearing by means of a ball bearing

Nowadays, the rotor shaft bearing is implemented by means of a ball bearing not only in race cars. For example, BorgWarner recently started using ball bearings in production.

Ball bearings and roller bearings can be used to achieve a very fast response (unlike with plain bearings) and the amount of lubricant required is reduced. A further advantage: one bearing unit can be used to absorb axial and radial forces. Reduced friction is noticeable on cold starting, and the turbocharger can be made smaller. Efficiency is increased and engine response is improved.

Ball bearings are becoming increasingly important in series production also due to the increasingly stringent legal limits for emissions. For example, SKF supplies ball bearing units for turbochargers. However, slightly higher manufacturing costs are one disadvantage of ball bearings.
3.3 Sealing the core assembly

The bearing housing and/or core assembly must be sealed against both gas forces and oil loss. This is achieved not by means of a lip seal, as is frequently mistakenly believed, but with piston rings that are fixed permanently in the bearing housing and do not rotate.

This is a contactless seal, comparable with a labyrinth seal. This makes it difficult for oil to escape by means of deflection and ensures that only a small exhaust gas volume can enter the crankcase.

Never remove the compressor wheel to carry out repairs to the turbocharger as the rotor (turbine, compressor, shaft) is finely balanced. This should be left to a special company with the appropriate machinery (such as a high-speed precision balancing system). The slightest damage to the rotor could very quickly cause major damage.

3.4 Charge air pressure control

Closed-loop control

We refer to closed-loop control when a defined set value is compared permanently with an actual value. If the actual value deviates from the set value, an actuator carries out corresponding readjustment until the value is (approximately) restored.

According to DIN 19226, closed-loop control is a procedure “in which a variable (the variable to be controlled), such as the temperature, speed or voltage, is recorded continuously and compared with a given value (the reference variable). Depending on the results of this comparison, there is adjustment of the variable to be controlled to the value of the given variable by means of the control procedure.” For example, the charge air pressure is monitored permanently by the ECU and correspondingly adapted dynamically depending on the defined load situation (multiple influence factors) of the engine.

Closed-loop control usually takes place as soon as a sensor is involved.

Open-loop control

We refer to open-loop control, as it were, when an input variable directly influences an output variable by means of specific laws in the system (multiple influencing factors may have an impact). Ignition time adjustment via a centrifugal governor or acceleration enhancement (carburettor) via the gas pedal position are examples of open-loop controls.

According to DIN 19226, open-loop control is “a procedure where an input variable influences an output variable in a predetermined manner. The open action flow in a single transmission component or a control variable is characteristic of open-loop control in its simplest form.”

Turbocharger control

If the engine speed increases, the exhaust energy and, inevitably, the turbine speed are increased, and hence the resulting air mass flow fed to the engine. The performance increases. However, there is a limit to what is desirable and technically feasible and appropriate. For this reason, it is necessary to regulate the turbocharger’s power output. This can be done in a variety of ways:
Illustration 13
Wastegate, including a spring-loaded diaphragm actuator (vacuum actuator) and rods. Illustration: Honeywell/Garrett

- on the exhaust side,
- on the fresh air side,
- via a combination of the two.

On the exhaust side, it is possible to dissipate surplus exhaust energy by means of a wastegate. Thus part of the energy does not reach the turbocharger turbine at all. The wastegate is connected to a pneumatic vacuum actuator via a control rod.

The wastegate opens at a certain pressure and diverts some of the exhaust gas around the turbocharger (overpressure system). This limits the charge air pressure. Opening of the valve is determined by the area of the diaphragm, spring, the valve surface to lever ratio and the pressure acting on the diaphragm actuator.

The high (exhaust gas) temperatures are the problem with this arrangement. Hence the valve flap in the exhaust manifold and the turbine-side diaphragm actu-

Illustration 14
Wastegate with overpressure regulation. Here, the charge air pressure actuates the vacuum actuator or wastegate flap via a hose. Illustration: Mario Köhler
In the case of the wastegate, the charge air pressure can be directed to the actuator via a hose from the compressor output side directly or via a 3-way valve.

Info

Blow-off/pop-off valves and divert air valves are not used to regulate the charge air pressure.

Turbochargers: Components, operating principle

In the case of the wastegate, the charge air pressure can be directed to the actuator via a hose from the compressor output side directly or via a 3-way valve.

If, for example, the hose is porous, cracked and leaking, the wastegate remains closed for longer and the turbocharger is no longer limited. The charge air pressure is exceeded. In modern engines, the engine management system switches to an emergency program once the set charge air pressure is exceeded by a certain amount and thus reduces the performance.

Blow-off/pop-off valves

Blow-off/pop-off valves

When the throttle is closed, charge air pressures are controlled by means of what are known as blow-off/pop-off valves (these are open systems in motorsport) or divert air valves (production vehicles, closed systems) on the inlet side or fresh air side respectively.

Blow-off/pop-off valves are a kind of protective function and prevent the compressor from "pumping". In the case of gasoline engines, the throttle valve is closed when the driver lifts off the gas and the compres-
The function of the blow-off/pop-off valves is identical to the divert air valve, apart from the fact that the air is directed into the open.

If the charge air pressure is too low and an error message “Charge air pressure too low” is generated, this may possibly be caused by a defective divert air valve. Experience has shown that in practice, this is frequently an indicator of a defect and the valve no longer closes correctly, or the diaphragm is torn.

3.5 The electrically actuated divert air valve

Kolbenschmidt-Pierburg, for example, has incorporated an electrically actuated divert air valve in the turbocharger with an integrated exhaust manifold. This component is available separately and can be replaced. This is an advantage for vehicle dealerships and workshop customers. Vierol subsidiary Vemo also supplies aftermarket divert air valves.

There are a number of advantages with electrical divert air valves. The component is compact and not very vulnerable. Pneumatic lines, the vacuum tank, the non-return valve and the electric switching valve are all omitted. Direct control means up to 70 percent shorter switching times, which is ideal for sporty turbo engines when loads change quickly. The electrically actuated divert air valve was launched in production vehicles in 2004 with the Audi 2.0 l Turbo FSI engine and the Volkswagen Golf V GTI.

Many drivers who are keen on motorsports fit what are known as open blow-off valves in place of the original divert air valve. This achieves the hissing sound so familiar in motorsport. The valves allow already compressed air to be blown off into the open when the gas pedal is released.

One known disadvantage is “confusion” of the engine control unit due to the “leaping” values of the mass airflow sensor. Blow-off valves contravene emissions legislation in many countries. In Germany, they are not removed approved during the general inspection.
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4. Turbochargers: Designs and variants

4.1 The classic turbocharger with wastegate

The simplest shape of a turbocharger is the variant with a bypass valve or wastegate. The turbocharger shaft and hence the turbine or compressor wheel rotate more and more quickly with increasing exhaust gas volume as the engine speed increases. The increase in speed is accompanied by increasing mechanical and thermal load on the components involved.

From a certain charge air pressure (defined by the mechanism or electronics of the control diaphragm), the waste gate is opened on the turbine side and leads the exhaust gas flow past the turbine and directly into the exhaust system (electronic charge air pressure control, see chapter 5.1). The turbine speed does not increase further. There is no other regulation option. The turbocharger virtually only works within a specific speed window. If the engine speed and hence the exhaust gas flow are too low, the turbocharger generates no additional performance (turbo lag).

4.2 The turbocharger with variable turbine geometry (VTG)

What is known as the VTG turbocharger (variable turbine geometry turbocharger) permits far more precise control of the charge air pressure. Up to now, this has mostly been used in turbocharged diesel engines in large-scale production. VTG technology is also becoming more and more common in gasoline engines due to downsizing tendencies (see chapter 5.5). A pioneer in this regard was Porsche, with its 911 Turbo from 2006 onwards.

In the case of the VTG turbocharger, the turbine performance is adjusted at the turbine wheel inlet by changing the inflow angle and velocity. This is achieved by means of appropriately designed guide vanes, which have an adjustable angle of attack. Thus at lower engine speed and little exhaust gas flow, but where high performance is needed, the exhaust gas is accelerated by means of smaller flow cross-sections and fed to the turbine blades. This increases the speed of the turbine and
hence the performance of the turbocharger. At high engine speed and hence high gas flow rate, the VTG vanes “open”, the inflow cross-section at the turbine is enlarged and the gas velocity is reduced. The turbocharger performance is thus reduced.

4.3 The twin-scroll turbocharger

What is known as the twin-scroll turbocharger is a special design. This is a turbocharger with a dual-branch turbine inlet. The exhaust gas flow is collected in an exhaust manifold designed especially for the turbocharger. In practice, in the case of a four-cylinder engine with the ignition sequence 1-3-4-2, this means: The exhaust gases in cylinders 1+4 are combined in one duct. The exhaust gases in cylinders 2+3 also pass through a shared duct. The geometry of the cylinder head and/or the exhaust manifold may vary. The advantage is the more homogeneous exhaust gas flow within each group of cylinders. The separate exhaust gas flows mean that the cylinders do not interfere with one another when ejecting the exhaust gases and the dynamic energy of the individual pulses is transmitted to the turbine wheel, without disturbance.
In the case of the twin-scroll turbocharger, one exhaust gas impulse is sent within a duct to the turbine wheel for every 360° crank angle (CA). If we look at both ducts, there is a smooth sequence of exhaust gas pulses at the turbine wheel every 180° CA.

Separating the exhaust gas flow creates two (smaller) ducts, each with a higher flow velocity. This turbocharging concept results in optimized transmission of the exhaust gas flows to the turbine wheel blades. This results in faster, more direct turbocharger response and hence more power delivery. As the cross-section of the exhaust manifold is limited, however, losses sometimes have to be accepted at peak performance. Examples of this include the BMW 335i six-cylinder turbo (initial series) with a conventional turbocharger and the 335i with a twin-scroll turbocharger.

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Classic turbochargers only have one admission port for all cylinders into the turbine wheel, which does not lead to a homogeneous exhaust gas flow under certain conditions. This may have an adverse impact on turbocharger response and performance.

A quick look: Exhaust manifold

Exhaust manifolds are no longer cast as “one piece”, but are manufactured – for example – as AGI (air gap-insulated) manifolds from specially alloyed tubing using the internal high pressure forming process. The air gap has an insulating effect and helps to reduce heat loss, while
The useful exhaust energy arriving at the turbocharger is higher. The double-walled design of the exhaust manifold means that it is not usually easy to detect a defective exhaust manifold in the workshop (the AGI manifolds sometimes have problems with regard to durability).

The exhaust manifold is integrated directly in the cylinder head in the engines of the future. As the central manifold is made of aluminum, this will also help to save considerable amounts of money.

### 4.4 Register turbocharging (alternating activation)

In the case of register turbocharging, two turbochargers of equal size, for example, or one large turbocharger and one small turbocharger are used (register turbocharging = alternating activation), and these can be engaged or disengaged as necessary. Thus a (smaller) turbocharger can compensate for “turbo lag” in the lower speed range, at low exhaust gas flow, until the more powerful, larger turbocharger is actuated. The engine exhibits spontaneous throttle response. Activation of the second turbocharger also reduces exhaust gas counterpressure. The engine has less work to do, thereby reducing fuel consumption. Register turbocharging is used only infrequently nowadays.

In practice, the Porsche 959 was the first vehicle in series production to use register turbocharging. This technology was devised by Kühnle, Kopp & Kausch (later BorgWarner). The individual phases and charge air pressure control strategies are explained below using this vehicle as example. Porsche referred to this system as PRA, Porsche-Register-Aufladung (Porsche register turbocharging). Regulation is made up of three phases:

#### Phase 1: One-turbo operation up to 4,000 rpm

All the exhaust gas flows through the first turbocharger, which supplies the engine with charge air pressure in the lower speed range. It must be mentioned here that
this is a six-cylinder boxer engine, i.e. with two rows of cylinders. Hence the exhaust gas from the second bank of cylinders is passed to the first turbocharger via a transverse pipe. The compressor and turbine switch valves are closed in the lower speed range.

**Phase 2: Regulated one-turbo operation between 4,000 rpm and 4,200 rpm**

In the second phase, the second turbocharger is supplied with exhaust gas, the exhaust gas only being used to allow the turbocharger to "start", so to speak. This takes place from the time at which the first turbocharger provides the desired charge air pressure and more exhaust gas is available than is needed. The wastegate is closed. The turbine switch valve regulates the charge air pressure. Hence the pressure of the second turbocharger is not fed directly to the engine, the compressor switch valve is still closed.

**Phase 3: Twin charger operation over 4,200 rpm**

The exhaust gas energy is now sufficiently high for both turbochargers. The compressor switch valve of the second turbocharger is opened. The bleed valve that supplied the first turbo with charge air pressure in the second phase is closed. Both turbos are now in use and the charge air pressure is only adjusted by means of the wastegate.

It is clear from this depiction how elaborate the regulation is. This technology dates back to the 1980s and was implemented mechanically by means of pneumatic actuators. A Bosch Motronic handled regulation management.

**4.5 Biturbo/twin-turbo charging (parallel connection)**

Biturbo or twin-turbo charging involves a parallel arrangement of two turbochargers. The two chargers are used over the entire load and speed range. In the case of a six-cylinder biturbo engine, each turbocharger only has to fill three cylinders. In the case of a V8 engine, each turbocharger supplies one bank of cylinders.

With this form of turbocharging, smaller turbochargers can be used in place of one larger turbocharger and hence have lower moments of inertia to overcome. This results in improved response. The turbocharger turbines are thus supplied with half the exhaust gas volume. Each turbocharger has its own wastegate. The total volume flow and charge air pressure result from the supplied and compressed air from both compressors. This means that each turbocharger has its own charge air cooler and the cooled air flows are combined in a Y-shaped intake pipe before the butterfly valve.

With biturbo charging, achieving approximate turbocharger synchronization presents a challenge. Therefore, the designs of the two turbos frequently differ. By the way, this essentially affects the entire intake and exhaust gas system due to the differing situation on the left and right-hand sides of the engine bay.

A turbocharger can even help to compensate for the differences in the overall system by being calibrated differently.

**Tip**

As has been found in practice, defective or stuck valves or flaps are frequent causes of problems with charge air pressure. Automotive experts should bear this in mind when carrying out troubleshooting.

**Tip**

In the event of a charge air pressure problem, the automotive expert should check first which turbocharger is delivering too much or too little charge air pressure. To do this, the total charge air pressure is determined (the total charge air pressure is significant for the ECU) and then the individual pressures are measured at each turbocharger. A pressure gage or vacuum gage (Mityvac) is used for this. Where possible, the automotive expert can also read off the parameters by means of a tester.

**Info**

In the case of a sequential biturbo, the two turbochargers are not driven constantly by the exhaust gases. The second turbo is engaged only when the relevant performance requirement arises.
The control unit (ECU) uses comparison of the set value and actual value. Thus the turbocharger with the greater performance has to compensate for the weaker turbocharger.

4.6 Two-stage turbocharging (series connection)

In the case of two-stage turbocharging or series connection, two turbochargers are connected one after the other. This differs from register turbocharging in that there is permanent interaction between both turbochargers. One high-pressure turbocharger and one low-pressure turbocharger are used.

The exhaust energy is passed to the turbine side of the high-pressure turbocharger in the lower speed range. The wastegate and the bypass valve are closed. The smaller high-pressure turbocharger takes over compression almost on its own.

The wastegate is opened at medium speeds, the low-pressure turbocharger is supplied with exhaust gas. This compresses the air and passes the precompressed air over the suction side of the high-pressure compressor, which acts as a booster. If the maximum charge air pressure is reached, limiting takes place by opening the bypass valve and the wastegate, which is already open. This allows a large proportion of the precompressed air from the low-pressure turbocharger to bypass the high-pressure turbocharger, feeding it directly to the engine. To summarize, this means that regulation takes place on the exhaust side and the fresh air side.

Example: R2S technology

BorgWarner’s R2S technology, as it is known, is used in current 2.0 l Volkswagen diesel engines, for example. Two-stage regulated turbocharging likewise involves two turbochargers connected in series. The system combines one variable turbine geometry (VTG) turbocharg-
Regulated 2-stage turbocharger technology (R2S) for Volkswagen 2.0 l diesel engines. Illustration: BorgWarner

Illustration 29
Operating principle for regulated 2-stage turbocharging (R2S). Graphic: BorgWarner

Regulated 2-stage turbocharging (R2STM)

According to BorgWarner, a special protective coating is used on the compressor wheel in order to withstand the high loads and aggressive particles. Controlled by an electric actuator, the VTG turbocharger demonstrates improved response in the low speed range, which results in a rapid increase in charge air pressure for almost immediate acceleration.

Both turbochargers operate in series as the engine speed increases, the larger low-pressure turbocharger gradually taking over. The high-pressure turbocharger is bypassed on the turbine and compressor sides from the
higher medium engine speed range. The turbo continues spinning as some of the exhaust gas still flows over the high pressure turbine. However, it does not contribute to the charge air pressure. If the engine speed is increased further, almost all the exhaust gas flow travels directly to the larger B03 turbocharger, which is now solely responsible for charging and so ensures consistent power delivery at high speeds.

4.7 The triple turbo

The triturbo or triple turbo system (R3S) developed by BorgWarner consists of two high-pressure turbochargers and a large low-pressure turbocharger.

The two high-pressure turbochargers are designed as VTG turbochargers. The variable turbine geometry is regulated by means of electrical charge air pressure actuators. The low-pressure turbocharger is controlled on the exhaust side via a wastegate.

In phase 1, when the triple turbo unit is started, the turbine control valve for high-pressure stage 2 (VTG) is completely closed. The exhaust gas (initially) acts only on the turbine wheel of high-pressure turbocharger 1 (VTG). The compressor wheel is made to rotate. According to BorgWarner, this ensures spontaneous buildup of charge air pressure and optimum, dynamic response. The intake air thus enters via the compressor for the low-pressure stage. This is hardly precompressed at low speed or in the low load range (it can also be optionally bypassed, as a minor “braking effect” may actually occur).

In phase 2 and at medium engine speeds, sufficient exhaust gas mass flow is present to generate charge air pressure in the compressor of the low-pressure stage in addition to the charge air pressure in high-pressure
Illustration 33
Mean pressure curves for the R2S and R3S turbocharger systems.
Graphic: BorgWarner

Illustration 34
R3S turbo for the BMW M-Performance engine.
Graphic: BorgWarner

M-Performance

R3S turbocharger technology made its debut in BMW’s M-Performance diesel engines. The 3.0 l engine has a maximum output of 280 kW, with maximum torque of 740 Nm. A 3.0 l diesel engine fitted with the R3S turbocharger system achieves performance improved by 25 percent and fuel consumption reduced by 8 percent compared with an R2S application, according to BorgWarner.

4.8 The quad turbo

A core element of the current BMW six-cylinder diesel engine (B57 platform) is a newly designed two-stage turbocharging system (R2S) (double register turbocharging) comprising four BorgWarner turbochargers. The new turbocharger system is used in the 750d xDrive, 5 Series, X5, X6, and X7 models.

The high-pressure and low-pressure areas both have two turbochargers. In this regard, one low-pressure turbocharger has been replaced with two smaller ones. According to BorgWarner, this ensures faster response without increasing system weight. The exhaust manifold is designed to guarantee the best possible flow control at corresponding thermal load.
In the lower speed range, a high-pressure turbocharger quickly generates charge air pressure in order to prevent turbo lag. The two low-pressure turbochargers are engaged at higher speeds. The second high-pressure turbocharger comes into play when full performance is demanded. The four turbochargers then work practically “hand-in-hand”.

Compressor housing cooling and an intermediate charge air cooler have been integrated in the low-pressure stage in order to manage the high charge air pressures. According to BorgWarner, the geometry and materials of the wastegate have been optimized in order to ensure that the component is fully sealed. The turbocharger for the second high-pressure stage, which remains on “standby” in certain operating ranges, presented a further challenge. A mechanical seal is used, as in the predecessor, to prevent oil entering the air system from the bearing housing of the turbocharger during standstill, according to BorgWarner.
4.9 Compressor/turbo combination (using the example of the Volkswagen TSI)

The abbreviation TSI is a protected Volkswagen designation and means “Twincharged Stratified Injection”. This involves twin charging with direct gasoline injection (the same thing is termed TFSI, Turbo Fuel Stratified Injection, at Audi).

This involved a mechanical compressor and a turbocharger (later just a turbocharger). This design made it possible to make the gasoline engine with 1.4 l displacement considerably smaller. Downsizing reduces internal
Turbochargers: Designs and variants

friction forces and the moving masses. Fuel consumption is reduced without resulting in losses of performance or torque.

The compressor

The compressor (rotary-piston supercharger which operates according to the Roots principle) is driven mechanically via a ribbed V-belt, not the exhaust gas flow.

The advantages of a compressor are the rapid build-up of charge air pressure, the generation of high torque even at low speeds and simple engagement via a magnetic coupling when required. No external cooling or lubrication are necessary either.

The "stolen" drive power of the engine is a disadvantage. In other words, the charge air pressure is generated as a function of the speed and then regulated. Hence some of the energy generated is lost (a turbocharger is driven permanently by the exhaust gas, so the efficiency is considerably better due to the use of exhaust gas energy).
In the case of the compressor, the high thermal load is a disadvantage. Moreover, in the case of an engine with less displacement, the charge air pressure generated in the lower speed range is insufficient to generate high torque. The compressor practically receives its drive power "out of the tank".

The compressor is engaged via a magnetic coupling from a minimum torque requirement and up to an engine speed of 2,400 rpm. The charge air pressure of the compressor is measured via the manifold absolute pressure sensor G583, while the butterfly valve control unit regulates the function. The turbocharger is "out of service".

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The turbocharger starts at 2,400 rpm to 3,500 rpm. The compressor is engaged as necessary. This is necessary, for example, when the vehicle is traveling at constant speed and then accelerates sharply. Without engaging the compressor, the slowness of the turbocharger would result in delayed acceleration (turbo lag).

From a speed of 3,500 rpm, the turbocharger generates the required charge air pressure alone in every operating state. It is regulated via the wastegate bypass regulator valve. (Source: Volkswagen, SSP 259)

4.10 The VNTOP turbocharger

What is known as the VNTOP turbo (Variable Nozzle Turbine One Piece), also known as Slide Vane, is a special turbocharger variant. The nature of charge air pressure regulation is similar to the VTG turbocharger as described previously, but the implementation is simpler and more cost-effective.

In the case of the VNTOP turbo, which was developed by Garrett, charge air pressure regulation takes place via a piston displaceable axially which adjusts the turbine’s inlet cross-section in relation to the axis of the turbocharger. Just an actuator is needed for adjustment of the inlet cross-section. Adjustment takes place pneumatically by means of a control pressure capsule. This technology was used in smaller PSA group diesel engines, for example, and is used infrequently nowadays.

4.11 Side glance: Turbocharger with water-cooled turbine housing

Continental began series production of the first passenger car turbocharger with an aluminum turbine housing. This unit has been integrated in the 3-cylinder gasoline engines for the MINI Hatchback since the spring of 2014.
While classic turbocharger designs with steel housings may glow red under full load, the aluminum turbine housing keeps “a cool head”, according to the manufacturer. A double-walled aluminum turbine housing surrounds the hottest area with a cooling water jacket. Thanks to the coolant flow through this jacket, the temperature of the housing surface never exceeds 120 °C, while internally the temperature should remain below 350 °C, according to Continental. Thus less effort is needed to provide thermal protection for adjacent components. Cooling the exhaust gas flow means that the catalytic converter is not under such high thermal load and hence ages less quickly. An electric actuator at the wastegate ensures that the catalytic converter heats up quickly.
5. Peripheral equipment, auxiliary functions

5.1 Electronic charge air pressure control

In general, the trend is moving away from pneumatically regulated charge air pressure control by means of a vacuum actuator towards electronic solutions. This affects both wastegate applications and the control of the adjustment ring in a VTG turbocharger.

Purely pneumatic regulation can only limit a defined full load pressure. In the partial load range, regulation is only partially possible (vacuum actuators supplied with a vacuum make this possible) as the pressure at the pneumatic actuator is simply insufficient to actuate the wastegate, for example.

Precise, pressure-independent modulation of the charge air pressure is only possible with finer electronic charge air pressure control. The charge air pressure can thus be set as a function of relevant parameters such as charge air temperature, injection parameters, fuel quality, etc. A modulated actuating pressure generated by a proportional valve acts on the wastegate actuator diaphragm. This operates at a frequency of 10 to 15 Hz. The spring preload is significantly smaller compared with the usual control so that corresponding regulation can be effected even under partial engine load, i.e. at far lower charge air pressures. In diesel engines, electronic charge air pressure control is often executed by means of a vacuum. (Source: Motair turbocharger).

5.2 The charge air cooler

The charge air cooler, also known as the intercooler, brings the air compressed via the turbo/compressor or G-Lader – which causes it to be heated – back to a reasonable temperature. The higher the temperature, the more the air expands; and the cooler it is, the more it contracts.
More oxygen is able to enter the combustion chamber when the air is cooler and has a higher density. More fuel can be injected, thereby increasing engine output. As a basic rule of thumb, reducing the charge air temperature by about 10 °C increases engine output by about three percent.

Compression by the turbocharger or compressor heats the air by up to 150 °C. The air reaches temperatures of up to 220 °C in the case of highly turbocharged diesel engines. Moreover, multistage turbocharging systems have an additional integrated cooler between the high-pressure stage and the low-pressure stage.

The compressed air can be cooled by up to 40–50 °C by means of a charge air cooler of correspondingly large size. In the case of vehicles such as the Subaru Impreza, the charge air cooler is also sprayed with water to reduce the temperature still further.

When replacing a defective turbocharger, the entire charge air circuit should always be inspected. If oil sludge and/or metal chips have penetrated the system, the charge air cooler must also be replaced. Cleaning the narrow cross sections is impossible, or inexpedient. Charge air coolers with turbulence inserts cannot be flushed or cleaned on account of their design. Charge air coolers in high mileage vehicles are frequently damaged by stones or dirt.
5.3 Speed sensors

Nowadays, some turbochargers come with speed sensors in order to supply the engine with the best possible airflow and improve performance. Monitoring the speed should protect the turbocharger from overspeeding. The objective is to extend the service life. Using a speed sensor also offers the option of reacting very quickly and precisely to changes in the environment, protecting the turbocharger from damage.

Corresponding speed sensors are suitable for both one-stage and two-stage turbocharging systems. It can be designed as an inductive sensor (passive sensor) or as an eddy current sensor (active sensor). Function diagnosis takes place by reading off the parameters or using an oscilloscope.

5.4 Swirl flaps/tumble flaps

Diesel and gasoline engines use what are known as swirl flaps or tumble flaps in order to improve the mixing (swirling) of the air-fuel mixture. These are located in the intake manifold and allow the movement of the aspirated air to be adapted to the relevant load and speed. Performance and torque are improved, and fuel consumption and harmful emissions are reduced slightly. These flaps are operated electrically or pneumatically, depending on the design.

In the case of problems with charge air pressure or performance and poor throttle response, the automotive expert should check the swirl/tumble flaps for contamination and make sure they move smoothly. Flaps may also come loose from the shaft on occasion, causing parts to enter the combustion chamber or become wedged.

The intake manifold flaps are closed at idle. The swirl flaps are opened gradually during starting and as speeds increase so as to ensure maximum performance and torque.
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6. VTG turbochargers for gasoline engines

About 10 years ago, the Porsche 911 Turbo was the first vehicle to be equipped with a BorgWarner VTG turbocharger for gasoline engines. Nowadays, numerous Porsche models use the fourth generation of this technology, including the Porsche 718 Boxster with its four-cylinder boxer engine.

The significantly higher exhaust gas temperatures (up to 1,000 °C) present a challenge for VTG technology in gasoline engines. New materials, an ingenious adjustment and bearing mechanism and new combustion processes make implementation possible. The advantages: All exhaust gas energy is used, the wastegate is omitted.

BorgWarner gasoline VTG for the volume market

BorgWarner supplies gasoline VTG turbochargers for the volume market as well. According to BorgWarner, the turbocharger with adjustable turbine geometry is optimized for new combustion systems and hybrid applications. The turbocharger is designed for the higher exhaust gas temperatures and should ensure improved response at low speeds, as well as direct and linear acceleration.

Moreover, the current VTG technology has an electric actuator that controls the pressure before the turbine by adjusting the guide vanes (S-Vane Design).
Bosch Mahle Turbosystems (BMTS) is aiming to use what is known as Floating Nozzle Technology (FNT) to increase the performance of gasoline engines as well. According to BMTS, consumption can be reduced by up to 20 percent using further refined turbocharged engines, even in the case of gasoline-driven vehicles and in view of the use of particulate filters. FNT involves further refinement of the variable turbine vane adjustment known as VTG technology. However, FNT for gasoline engines results in a solution that is more compact, according to BMTS controllability is improved and the system has less of a tendency to jam while maintaining identical guide vane clearance. This technology uses the “floating principle” (doing without a solid cage, there is merely a cover plate resting on spacers) to ensure higher thermal shock resistance at temperatures of up to 1,050 °C, which occur in gasoline engines.

The wastegate is omitted

The wastegate turbochargers used to date in gasoline engines compensate for the increased exhaust back-pressure brought about by the particulate filter by means of a larger turbine wheel (from 2017, the Euro 6c standard defines more stringent requirements for particulate limits for gasoline engines as well). However, the larger, heavy turbine wheel removes some of the dynamism and torque of the engine on account of the higher mass inertia. Some of the exhaust energy is not used. The gasoline VTG technology replaces the wastegate: the turbine wheels can be made more compact.
Electrical compressors, unlike conventional turbochargers with turbines, have the advantage of being able to regulate the charge air pressure independently of the exhaust energy available. This helps to improve performance and the engine efficiency can be increased.

While the turbocharger is designed with performance in mind, the electric variant independent of engine operation improves spontaneous response by means of particularly fast charge air pressure buildup. Hence this is an appropriate alternative to multistage turbochargers, which are frequently very expensive and require a lot of space. The electrical power needed to build up charge air pressure can also be made available entirely or partly due to the higher recuperation performance of the 48 V system. This also helps to improve efficiency.

Moreover, electrical compressors combined with conventional turbochargers ensure that turbo lag is largely compensated for at lower speeds.
For instance, BorgWarner has furthered the development of what is known as the eBooster into series applications. This electrically assisted charging system uses a rotodynamic compressor driven by an electric motor as a component before or after a turbocharger. Unlike the electrically assisted turbocharger, this system operates at a two-stage level, as two turbomachines connected in series. This multiplies the pressure ratios of both charging units.

Using two coordinated rotodynamic compressors makes it possible to adapt the entire system optimally to the intended purpose and to extend its overall performance map entire duty chart. Beside the eBooster and turbocharger are separate units. The advantage of this is that the thermomechanical load of the electrical and electronic components is significantly smaller in the case of corresponding positioning than is the case with the electrically assisted turbocharger.

According to BorgWarner, the eBooster permits the development of small and efficient high-performance turbocharged engines where the dynamic response matches that of large non-supercharged engines of the same power output.
8. Turbocharger troubleshooting

8.1 Smoke

Blue smoke is caused by the burning of oil. This is caused by excessively high flow resistance in the intake system, leaks before the turbine, a defective piston ring seal, or blocked or deformed crankcase ventilation. The following must also be considered:

- a coked turbocharger bearing housing,
- a contaminated air filter system,
- blocked oil lines,
- damaged bearings at the turbo,
- worn engine/cylinder liners,
- defective valve stem seals, defective piston rings
- increased blow-by,
- contamination in the charge air cooler or intake duct.

White smoke is nothing more than water vapor. This is caused by water in the exhaust system on account of driving short distances, a defective cylinder head gasket or a defective AGR cooler and a defective intake manifold (flushed with water). White smoke located just above the ground indicates uncombusted fuel. This is caused by a faulty injection system.

Black smoke is caused by too “rich” a mixture. In other words, too much fuel is being combusted in relation to the amount of air.

Tip

Smoke diagnosis, as it is known, is always useful in the workshop. A diagnostic device for smoke can be used to trace any leaks. These are available from Bosch (the SMT 300), Normteile (the Smoke Wizard GLD-40), Hella Gutmann (the SLD Tool) or Snap-on (the EELD 100A), for instance. Catalytic converters and particulate filters may sometimes make it more difficult to search for the leak.

8.2 Noise

If the turbocharger makes noises (whistling, buzzing) while the charger pressure is building up, the automotive expert first checks all hoses and connections to locate any damage and to ensure that they are sealed. A
Turbocharger troubleshooting

certain amount of dismantling is necessary for this. Leak detector spray or an emissions analyzer can help to locate some damage.

Leaking sealing surfaces on the exhaust manifold side, worn-out turbocharger journal bearings or the turbocharger shaft itself are all critical points.

8.3 Engine oil, oil loss and lack of lubrication

One of the most common causes of turbocharger failure are problems with the oil supply or lack of lubrication of the rotor and journal bearings. Hence the following points must be noted as a matter of urgency:

1. Using the correct engine oil and topping up to the correct level are absolutely crucial. A substandard oil that does not meet the manufacturer’s standards or an oil of a different viscosity class and with other additives may damage the turbocharger. This is why: The turbocharger’s bearing surfaces

Multiple turbochargers have already been replaced in vain. However, the whistling noise originated from a leaking exhaust manifold. A stud bolt may also be damaged. It is worth checking more closely.

Diagnostic matrix

An overview – like the diagnostic matrix shown in the illustration – may help you to find any turbocharger system faults quickly. In other cases, and depending on the age of the vehicle, it may be worth reconditioning a turbocharger. Special companies such as BorgWarner (Reman program), Motair or BTS Turbo, or specially qualified vehicle workshops, can do this.
are merely separated by a thin film of oil, 0.02–0.06 mm thick. As soon as this film of oil is interrupted, there is immediately massive wear on the shaft and bearings. The oil change intervals specified by the manufacturer must be observed without fail.

2. The oil pressure must be correct, guaranteeing a bubble-free supply of oil from the oil pump.

3. The banjo bolts used for fixing the oil supply lines must be checked for cleanliness.

4. The automotive expert can measure the internal engine pressured to check whether the oil is able to return to the sump without pressure. If this is not ensured, the oil will back up into the turbocharger. The oil may travel via the rotor shaft seals into the intake and exhaust system. This will result in loss of oil. Blocked return lines, oil separation systems blocked with coke or sludge and engine components worn due to aging, blow-by gases or thinning of the oil are responsible for this.

5. Are all sealing elements involved fine? Damaged seals may, for example, result in coke deposits due to particles entering the engine oil; e.g. via the exhaust gas recirculation duct or the valve cover into the interior of the engine (sample case: BMW X3 2.0 diesel).

6. When a new turbocharger has been installed, the turbocharger system must be prefilled with oil.

Many vehicle manufacturers have extended their service intervals, frequently resulting in increased residues in the engine. If the defective turbocharger has to be replaced, the automotive expert also checks the sump for deposits.

Liquid sealants (Curil) and exhaust assembly compounds have no part to play in turbocharger systems! Exhaust sealing compounds may mechanically destroy the turbine wheel. Liquid sealants may block the oil circuit and bring it to a standstill. The manufacturer’s installation instructions must also be followed in any case.

Water, soot, dust and combustion residues collect in engine oil over time. In diesel engines in particular, combustion residues alter the viscosity. This results in wear to the bearings and piston rings in the turbocharger. This leads to extremely high oil consumption, culminating in damaged turbines and compressor vanes. If the engine draws in pieces of metal, this may result in catastrophic engine damage.
Turbocharger troubleshooting

The automotive expert only replaces a turbocharger together with a new oil supply and return line, as well as a new engine venting unit (recommended by numerous manufacturers, such as BMW). It also goes without saying that both the oil filter and air filter must be changed. It is not possible to clean the said components, nor is this a promising thing to do. For instance, Schlütter offers the “166 Turbo Pro Kit Program”. Besides the original turbocharger, this contains the corresponding oil supply lines (www.turbolader.com).

Practical example: Turbocharger damage due to inadequate oil supply

As indicated in workshop practice, the 1.6 l diesel engines designated “DV6” and DLD-416 (to Model Year 2013) repeatedly suffered early turbocharger damage. The engine (DV6) developed by car manufacturer PSA is used in models from Citroën and Peugeot, as well as vehicles from Fiat, Volvo, BMW (Mini), Mazda and Suzuki. This engine is designated DLD-416 in Ford vehicles.

Due to their experiences, numerous experts caution against merely replacing the turbocharger on these engines. There is too great a risk of it “fragmenting” the compressor again after a short time. This is why: Bearing damage at the turbocharger is increasingly common with the said diesel engines due to a lack of oil supply. According to service information issued by BTS Turbo (SI-130619), this lack of lubrication is caused by metal abrasion and severe soot deposits impeding the flow of oil. Motair, another company specializing in the sale of turbochargers, describes the causes in a similar fashion. The turbocharger experts unequivocally blame a lack of lubrication for cumulative turbocharger defects in this PSA engine type.

Info
Turboprotect (www.turbo-protect.com) offers an additional oil filter for the PSA Group 1.6 l diesel engine which ought to prevent turbocharger damage as long as the cleaning intervals are observed accordingly.

Info
Among others, HBT-Spezialwerkzeug has a tool for the PSA engine in question in order to restore and clean the injector shaft in their program (www.hbt-spezialwerkzeug.de)
Attempts should not be made to look for the cause in the direct vicinity of the turbocharger; rather, you should be looking for leaks between the injector and the combustion chamber. A copper ring that seals the combustion chamber from the injector leaks. Exhaust gases and unburnt diesel can enter the camshaft housing. The two media mix with the engine oil here. This results in a chemical process which decomposes substances under the influence of temperature. As a result of this, the properties of the engine oil change and parts of the lubricant “slag”. The turbocharger shaft no longer receives enough lubricant and runs hot, resulting in total failure.

By Rudolf Guranti and Torsten Schmidt (extract from a Krafthand contribution, appearing in the Edition 12/2016)

The formation of condensation, carbon deposits and ash is frequently attributable to poor oil quality.
8.4 Material defects, production, quality control

As with all technical components, material defects are not impossible even in the case of turbochargers. Throughout my entire career as an automotive expert (the author), I have been made aware of almost no pre-existing damage of this kind to the turbochargers of renowned manufacturers such as BorgWarner, Garrett, Bosch Mahle Turbo Systems (Mitsubishi (MHI), IHI Charging Systems, Aisin or Continental with a low market share).

Series turbocharger production is a complex process. It begins with the extremely precise manufacture of the castings (chassis) and affects the bearings and shaft and, above all, the turbine and compressor wheels. The manufacturing tolerances are in the micrometer range to some extent.

Know-how in the field of quality management (QM) is also at a high level among the market leaders. For example, so-called end-of-line tests are carried out by BorgWarner in Kirchheimbolanden as part of their QM management. In other words: production parameters and balance values are checked in a fully automated process at the end of the production line in order to confirm the functional capability of each and every turbocharger. All data is saved by component.
8.5 Foreign objects, turbine-side

Flow of exhaust energy into the (drive) turbine of the turbocharger takes place radially. Hence damage is not readily apparent, even with the turbocharger removed. Further dismantling work is required. Using an endoscope or mirror may sometimes help.

The resulting imbalance will destroy the turbocharger sooner or later, which may eventually result in the shaft being torn off or even engine damage.

8.6 Foreign objects, compressor-side

The air drawn in enters axially at the compressor. As a rule, the damage to the compressor wheel can be seen clearly (after removal of the intake duct). Worn air filter elements or contaminated air filter box, for example, may cause this.

As the turbocharger compressor wheel is made of a (relatively) soft aluminum alloy, just the tiniest foreign objects are enough to damage it and cause imbalance in the rotating system. This causes problems with the bearings and may cause the rotor shaft to be torn off. There is also the potential for engine damage. This is why the air filter must be checked regularly and replaced where necessary. The air filter box must be clean.

Special case

A special case occurs when the nut of the compressor wheel becomes loose or comes off completely. There is no manufacturing fault. If the shaft nut comes loose, this is due to a lack of oil and brief seizure of the rotor shaft. The compressor wheel continues to rotate. In the case of turbochargers rotating clockwise, there is a left-hand thread on the compressor wheel (the line of sight is from the intake duct to the compressor wheel).
Turbocharger troubleshooting

8.7 Loss of performance

A turbocharger is primarily dependent on the exhaust gas flow that flows through it and drives it. By exhaust gas flow, we mean the enthalpy stream; i.e. the internal energy of the emerging exhaust gases. The enthalpy stream ($U_1$) is calculated using the pressure and the volume ($V$), $U_1 = p_1 \times V_1$. There may be several reasons for loss of performance.

The most frequent causes of loss of performance:

- sticky adjustment vanes on the VTG turbocharger. The charge air pressure set point/actual comparison is outside tolerances, the ECU switches to limp mode.
- defects in the charge air pressure control circuit (leaky pressure capsule, vacuum hoses that have slipped off or broken, broken electrical connections).
- defective wastegate valves. The turbine is not receiving the full exhaust gas flow.
- rotor shaft blockage caused by a lack of oil (see also chapter 8.3).
- defective turbine wheel caused by damage due to foreign objects or overloading (see chapter 8.5).
- a damaged compressor wheel caused by foreign objects (see also chapter 8.6).
- leaks between the intake manifold and the turbocharger. The charge air pressure is lost. This results in hissing and whistling noises.
- blocked exhaust or intake system.
- a defective injection system.
9. Counterfeit products and risks

Counterfeit turbochargers are always appearing on the market. There are frequent complaints about their lack of quality. Failure to meet tolerances, cleanliness requirements and the use of inferior alloys are fundamental problems.

The products are placed in what is supposed to be original packaging or bear the relevant trademark or a forged name plate and registration number. In most cases, the much lower purchase price should be cause for suspicion.

Parts supplied by customers

Essentially, the automotive expert should avoid installing parts supplied by customers. This is particularly true of components such as the turbocharger, which are critical to the function and relevant to safety. “Alternative products” are frequently sourced from the Internet. Price has a dominant part to play. If the automotive expert does not wish to reject parts supplied by the customer per se, he has to safeguard himself accordingly, in writing.

Krafthand has grappled with the subject of “parts supplied by customers” in the special issue “Workshop practice” (Krafthand-Magazin supplement, 04/2017). Video comments from workshop experts verify the critical handling of this topic.
Counterfeit products and risks

“The manufacturers of these counterfeit products consciously attempt to mislead consumers and use fraudulent labeling to give an impression of quality that is simply not present”, said a BorgWarner representative. To reveal the severe deficiencies in these replicas, BorgWarner examined two turbochargers at its in-house research laboratory and subjected them to extensive tests. "The replicas achieved nowhere near the high quality standards of the original BorgWarner turbochargers. This could place vehicles and drivers in danger”.

While the original turbochargers in this case are designed to operate at up to 180,000 rpm, the counterfeits – according to the data – failed to exceed speeds of 83,360 rpm and 100,000 rpm. Consequence: a short turbocharger life, as the counterfeiters obviously designed the bearings of the rotating equipment incorrectly.

According to BorgWarner, the two products compared also differed clearly in terms of balancing. Modern systems and an elaborate procedure at the end of the production process help to balance the compressor wheel of the original BorgWarner turbocharger. The counterfeit, on the other hand, are balanced by means of improvised holes and lead filling, regardless of the fact that using lead in vehicle components is prohibited throughout the European Community.

Illustration 84
The replica turbo is missing – for example – the green color marker on the shaft nut that is present in the original BorgWarner turbochargers.
Illustration: BorgWarner
10. Tips and tricks for workshop experts

10.1 Testing electropneumatic valves

The charge air pressure is frequently regulated via what are known as electropneumatic valves. The three connections are designated by means of color rings (white = vacuum, blue = actuating pressure, black = ambient air) or molded as shown in Illustration 84.

Illustration 85
An electropneumatic valve with symbols for the connections for vacuum, actuating pressure and ambient air.
Illustration: Mario Köhler

The electropneumatic valve is controlled by the engine control module by means of a PWM (pulse width modulated) signal and generates the actuating pressure from ambient air and vacuum. The valves are tested as follows:

1. carrying out a visual inspection
   a. correct tubing,
   b. correct connection,
   c. correct ventilation via a filter for the ambient air connection,
2. reading the DTC memory,
3. checking the vacuum by means of a pressure gauge on the vacuum input,
4. checking the actuating pressure at the actuating pressure output,
5. carrying out an actuator test and testing correct control by means of an oscilloscope,
6. testing the valve using a multimeter.

Illustration 86
A pressure gauge for setting the pressure of the wastegate valve.
Illustration: Motair
Tips and tricks for workshop experts

Testing a pressure-controlled wastegate turbocharger

The valve is “normally open” in the case of a wastegate turbocharger regulated by means of an electropneumatic valve. As a result, the wastegate vacuum actuator receives full actuating pressure at low duty cycle. No charge air pressure can be built up. The valve is closed at high duty cycle. Maximum charge air pressure is built up.

de-energized = open = full actuating pressure at wastegate = low charge air pressure.

energized = closed = no actuating pressure at wastegate = high charge air pressure

Testing a vacuum-controlled VTG turbocharger

The valve is normally closed in the case of a VTG turbocharger regulated with an electropneumatic valve. Hence the VTG adjustment actuator receives no vacuum at low duty cycle. Hardly any charge air pressure can be built up. The electropneumatic valve is open at high duty cycle. Maximum charge air pressure is built up.

de-energized = closed = no vacuum at capsule = low charge air pressure

energized = open = vacuum at capsule = high charge air pressure

10.2 The mass airflow sensor

All modern injection systems in both diesel and gasoline engines need to know at least the engine speed and the engine load/driver’s wishes. In systems with mass airflow sensors, like the ones built into TDIs, CDIs, and so forth, the charge air pressure generated is directly proportional to the mass airflow.

Tip

A defective intake hose after the mass airflow sensor may result in incorrect regulation of the AGR system, depending on the system. This means that the AGR valve does not close even under full load as the maximum mass airflow is not detected by the ECU. This results in coking of the intake area and the engine, which in turn may damage the turbocharger.

Tip

A low charge air pressure always results in a low mass airflow. This is why the automotive expert should always use a measured value block to carry out a set-point/actual comparison of the values of the mass airflow sensor and the charge air pressure (if provided by the manufacturer) in the event of a charge air pressure problem.
10.3 The particulate filter

Turbocharger damage is becoming increasingly common due to additional exhaust systems resulting from increasingly strict exhaust emissions standards. This is because of clogged particulate filters, due to regeneration cycles not carried out. Hence the correct function of the injection system must also be insured.

The exhaust backpressure at the turbocharger increases due to a blocked particulate filter. In a worst-case scenario, this may cause the axial thrust from the turbine wheel onto the thrust bearing to disrupt the film of oil, resulting in bearing damage.

10.4 Engine ventilation, the crankcase

If a turbocharger is replaced due to oil loss, the crankcase pressure must also be measured. A visual inspection is not conclusive; nor is it possible, as we are dealing with the mbar range. An elevated crankcase pressure will cause loss of oil at the turbocharger’s piston rings. The oil cannot return to the sump unhindered.

Repeated overloading of the particulate filter by traveling extremely short distances or using fuel of poor quality will lead to complete failure of the particulate filter sooner or later. Cleaning is not always possible due to the accumulation of ash in the particulate filter. Therefore, when carrying out diagnosis or repair the automotive expert will keep a careful eye out for the backpressure in the exhaust system. A test drive with a clogged particulate filter may possibly damage the turbocharger.

Incorrectly designed sports exhaust systems with dubiously low prices have generally proven very frequently to be responsible for turbocharger damage.

Impact on vehicles with VTG/VNT turbochargers: If the oil passes the piston rings and reaches the adjustment vanes of the turbine, it is combusted there. This results in soot deposits. These deposits may cause the adjustment vanes to enable limp mode (due to the desired slight clearance in view of the metallic thermal expansion). The setpoint/actual comparison of the charge air pressure no longer matches.
11. Replacement turbochargers, preparation

Manufacturers (original equipment suppliers) of turbochargers provide their own aftermarket program of OEM quality equipment or refurbish used turbochargers of third party makes. The latter ensures that repairs can be carried out to older vehicles that are commensurate with the value of the vehicle, as well as meeting the needs of workshop customers. The exchange programs specifically for automotive aftermarket purposes are known as “Reman programs” (BorgWarner) or, for example, Original Reman (Garrett by Honeywell).

Furthermore, some companies have specialized in the refurbishment of turbochargers.

Know-how counts

Some “classic” workshops which have the correct equipment and corresponding know-how are able to refurbish turbochargers, depending largely on what kind of damage has been sustained. However, in this case it is always important to note that years of experience, the necessary equipment, absolutely accurate and clean working and the use of OEM parts are crucial.
BorgWarner’s Reman program

BorgWarner’s Reman turbochargers are remanufactured original turbochargers. According to information provided, each turbocharger is initially dismantled so that as much material as possible can be reused. In another process, the parts are cleaned and reconditioned. Following the balancing process and thorough testing, every BorgWarner Reman turbocharger meets the same high quality standards as the brand new OEM models.

The remanufacturing process in detail:
- Controlled dismantling
- Automatic ultrasonic cleaning
- Measurement to ensure that the parts meet the specification
- High-temperature cleaning and shot-blasting of the turbine housing
- Part recycling and preparation
- Balancing the shaft and wheel
- High-speed balancing of the core assembly
- Replacement of all worn bearings and seals with OEM-quality new parts
- Fully inspected assembly
- Extensive quality tests throughout the entire process
12. Diagnosis and tuning on a dynamometer

Perfect diagnosis of an engine, including peripheral equipment and turbochargers, is most definitely possible if you are the lucky owner of a dynamometer. The automotive expert is capable of logging all relevant data and measurements.

Every speed and every load point of the engine can be reached under load. There is no longer anything to prevent targeted diagnosis. Furthermore, it is possible – with the right know-how and equipment – to adapt a (different or modified) turbocharger to the engine for sporty performance.

12.1 The compressor and turbine performance map

The compressor map

The performance and efficiency of a turbocharger are described by means of performance maps. The compressor map describes the pressure ratio over volume and mass flow rate. The usable map range of rotodynamic compressors is limited by the surge and choke lines and the maximum permissible compressor speed.

The surge line

The surge line limits the left-hand side of the duty map. If the volume flows are too small and the pressure ratios are too high, the flow detaches from the compressor vanes or in the diffuser. The conveyance of air is interrupted. The air flows backwards through the compressor until a stable pressure ratio is restored with a positive volume flow. The pressure builds up again. The process is repeated in rapid sequence. The term “surge” is derived from the noise this makes.
Diagnosis and tuning on a dynamometer

The choke line

The maximum volume flow of a radial compressor is generally limited by the cross-section of the compressor inlet. If the air in the compressor inlet reaches the speed of sound, no further increase of the throughput is possible. In the compressor map, the choke line is indicated by the steeply descending speed lines at the right-hand side of the map.

The turbine map

The performance of a turbine wheel is indicated in a turbine map. The mass flow lines and turbine efficiency are shown for various speeds. To simplify matters, both the progression of the mass flow and the efficiency can be approximated using a mean curve.

Turbine performance increases with increasing pressure drops between inlet and outlet. This means that the turbine performance increases when more exhaust gas “accumulates” before the turbine on account of a higher engine speed. Turbine performance also increases with increasing exhaust gas temperature. This is due to the higher energy content (>T) of the exhaust gas.
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Turbochargers
in the workshop
Technology, variants, troubleshooting

In Volume 17 of the KRAFTHAND Practical Know-how series, Mario Köhler describes the various technologies, the operating principles and the most frequent causes of damage to modern turbochargers. He also illustrates turbocharger technology in both diesel and gasoline engines.

Initially, Köhler outlines the history of the turbocharger and then continues with the latest technology. He describes various types and components. He takes a detailed look at turbos with wastegates, twin-scroll turbos and VTG turbos, for instance, and also describes various multi-stage charging variants.

Another chapter relates to the electrical compressor and VTG turbo for gasoline engines.

In the second part of the brochure, Köhler describes common turbocharger failures, shows pictures of damages and takes a look at the potential effects. Another chapter is devoted to the causes of turbocharger failures. Köhler provides workshop experts with tips and tricks and takes a look at fault diagnosis.

To conclude, this specialist brochure includes supplementary sections on subjects such as replacement and preparation, as well as counterfeit products.

“Essentially, Mario Köhler works with the very latest turbocharger technology and problem areas as part of his everyday workshop routine. I can definitely recommend this publication.”

Markus Krawczyk,
Managing Director of NGC-Turbotechnik, Eckental

The author
Mario Köhler is a trained mechatronics expert. He underwent further training to become a service technician for two-wheelers and is a certified business economist (HwO). Köhler has been working for his parents’ motor vehicle company since 2004. He has acquired numerous additional qualifications by taking extra courses. Turbochargers are one of his core specialist fields.