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Overview of boosting options for future downsized engines

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Driven by a demand for better fuel economy and increasingly stringent emissions regulations over a wide range of customers and applications, engine manufacturers have turned towards engine downsizing as the most potent enabler to meet these requirements. With boosting systems becoming ever more numerous as the technical solutions to complex boosting requirements of the internal combustion engine increase, it is time for an overview of available and under development boosting technologies and systems and for a discussion of their relevance to downsizing efforts.The presented analysis shows that there are no standard solutions for all the different applications as the trends indicate a rising complexity to meet with the extreme boosting requirements predicted for the remainder of the decade. These trends include variable geometry, a shift from single to two (or more) stages, extensive actuation for bypassing exhaust flows, exhaust flow regulation and pulsating exhaust energy recovery, severe electrification and an extensive effort downstream from the turbine to capture waste heat after the principal turbocharger/supercharger system.

engine downsizing, boosting technologies, boosting system

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1 Introduction

The need to reduce carbon dioxide (CO_2) emissions and fuel consumption is still the primary requirement in internal combustion (IC) engine development. The position of the IC engine as the engine type of choice for continued development seems to be unaffected by the advent of alternative propulsion systems (such as hybrids and fuel cells) and will probably remain so until at least well into the next decade [1].

With practically all new diesel engines featuring boosting systems and a projected 25% of all new gasoline engines in Europe also featuring boosting systems today [2], the relevance of boosting systems as an enabler for reduced emissions, fuel consumption reduction and improved performance is clearer. The most capable emission reduction technology today is engine downsizing combined with boosting technology. The advanced boosting systems of today are an essential feature of downsizing and the main enabler. The turbocharger (and to a lesser extent in terms of efficiency, the supercharger) is an inherent downsizing technology regardless of the type that is used in practice as it increases boost levels above ambient thus forcing more power out of a given size of engine.

Future projections indicate a shift to ever smaller engines. Most manufacturers are now downsizing engines from 2 litres to 1.3 to 1.4 litres in order to save fuel, as well as to reduce emissions [2]. Engine downsizing is also the most cost-effective method of emissions reduction. This trend is confirmed for both gasoline and diesel engines in projections to 2016 [1]. The scope for gasoline engine reductions is greater than for diesel, which will be discussed in the following section. Downsizing is an enabling technology for increased engine performance as a result of the higher spe-

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cific load (BMEP), not the increased speed, at which it forces the engine to operate.

The principal advantages of downsizing are a significantly increased power and torque for the engine without increasing the capacity of the engine or conversely the ability to reduce engine capacity while keeping engine power at the same level as a larger equivalent. The principal effect, therefore, of downsizing is an increased power density for the engine with an end objective of significantly reducing fuel consumption as well as CO_2 emissions [3].

The end objective of reduced fuel consumption is enabled through the reduced level of friction, reduced heat transfer across the cylinder walls and reduced pumping losses present in a downsized engine.

The main limitations to increased BMEP levels are customer acceptance cost, engine compression ratio (knock), engine thermal resistance, engine wear and turbo/supercharging response time.

In this paper, the boosting requirements are addressed, the available and under development systems are presented and the suitability of each one analyzed in relation to the engine requirements and in comparison to the other boosting systems.

2 Future boosting requirements

The main, general OEM needs for both gasoline and diesel engines are the ability of the boosting system to provide high BMEP, EGR rates and efficiency throughout the operating range, reduced and/or variable back pressure, rapid transient response, altitude performance, downsizing, downspeeding, hybrid powertrains and waste heat recovery [4].

2.1 Diesel engines

Diesel engines have been aggressively downsized over the past decade by up to 40%. The enabling technology has been primarily the single stage, wastegated or variable geometry turbocharger. The trend that was followed by diesel engines over the last decade is expected to be seen in gasoline engines.

Figure 1 shows the current and projected requirements in CO_2 emissions and fuel consumption terms for both gasoline and diesel engines. Diesel engines have now reached a stage where further downsizing will only be in the premium segment of vehicles that still feature engines in the 2.5 to 3.5 litre displacement bracket. Aggressive downsizing in diesel engines tends to increase the specific load, which, in turn, increases the oxides of nitrogen (NO_x) emissions from the engine. With increasing concern to reduce NO_x emissions and particulate matter, further downsizing of diesel engines could now be of less importance, as the emphasis shifts dramatically toward exhaust after-treatment solutions. By 2016, diesel engines with displacements higher than 2.0 litres are likely to have a low market share of less than 10 percent (of diesel engines), whereas diesel engines in the displacement bracket of 1.5 to 2.0 litres are likely to witness an increase in market share [2].

Diesel engines are projected to move up to 60% efficiency in 2014 compared to 38% in 2004, through waste heat utilisation, of which various super/turbocharger and power turbine combinations will play a central part in the downsizing

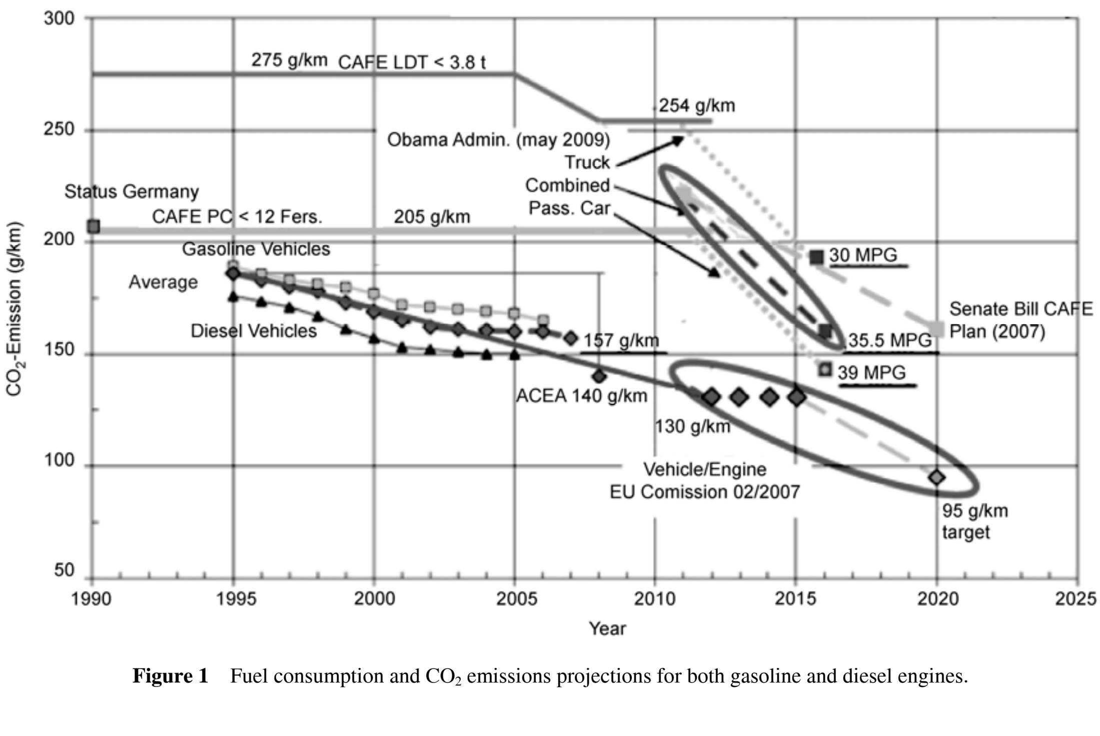

Figure 1 Fuel consumption and CO_2 emissions projections for both gasoline and diesel engines.

process [5].

For the next ten years, engine manufacturers around the globe will be providing engines with full load EGR rates between 0% and 30% and turbocharging systems must be available to suit these.

With increasing EGR and BMEP comes an increased requirement for boost pressure. At some stage, this becomes too high to achieve with a single stage compressor and two stage systems must be utilized [4].

2.2 Gasoline engines

Meeting customer performance expectations has resulted in CO_2 emissions for gasolines engines significantly worse than global objectives. The dominant technology trend to solve this problem is downsizing (as described earlier). A number of issues arise, such as knock mitigation and very high boost levels, which need to be addressed for the technology trend to be continued in the current decade and beyond. Resolution of these issues will enable future class leading, fuel efficient gasoline engines to be achieved. A target CO_2 reduction of 35% is a medium term requirement for a large vehicle to achieve the required fleet averages.

A state of the art, capacitive boost system will be required to provide up to 5 bar boost, in the medium term, over a broad speed range. Gasoline boosting systems today are limited to approximately 3 bar while the dynamic range, efficiency and driveability required will have to be improved given the specific targets of the NAIGT roadmap. Existing twin turbo or turbo-supercharged systems do not have the capability required. Figure 2 indicates the the current BMEP levels in production today and the near future, rising trend. Equivalently, current levels of BMEP over the engine speed range (for GDI engines) typically peak at 25 bar. Under development, highly boosted examples have surpassed 30 bar and a projected 30–40 bar BMEP operating range is indicated as a goal for this decade.

3 Downsizing technology enablers

In this section the main, key technologies in use today or under development are presented. Individually or in combination, these technological solutions offer the backbone on which the several different boosting systems (presented in the following sections) are based.

3.1 Turbine technologies

3.1.1 Variable geometry

The key to turbocharging is to maximise and control the boost pressure over as wide a field of engine operation as possible. VGT uses a turbine stage where the swallowing capacity is automatically varied while the engine is running. This permits turbine power to be set, providing sufficient energy to drive the compressor at the desired boost level wherever, in its range, the engine is operating. This is achieved by varying the area of a nozzle; a set of guide vanes or sliding nozzles that control the flow of exhaust gas through the turbine (Figure 3).

Reducing the inlet area increases exhaust manifold pressure and increases the turbocharger speed. As the nozzle ring opens up, the exhaust pressure reduces and the turbocharger boost decreases. In effect it creates an infinite number of fixed geometry turbochargers.

Among the benefits of VGT are a much improved transient response and fuel economy, increased useful engine operating speed range, enhanced compression brake capability, increased useful engine operating speed range, reduced engine swept volume and package size for a given rating and improved assistance to the operation of the Exhaust Gas Recirculation system (EGR).

3.1.2 Active (flow) control

The Active Control Turbocharger is a novel type of VGT and consists of an active control method of operation of a nozzle (similar but lighter to a VGT nozzle) at the turbine inlet with the aim of harnessing the dynamic exhaust gas pulse energy emanating at high frequency from an IC engine, in order to increase the engine power output and reduce its exhaust emissions (Figure 4). The technology was developed with the view to offer a new option in meeting with the demands imposed on the automotive industry by its customers and by ever more stringent emissions legislation.

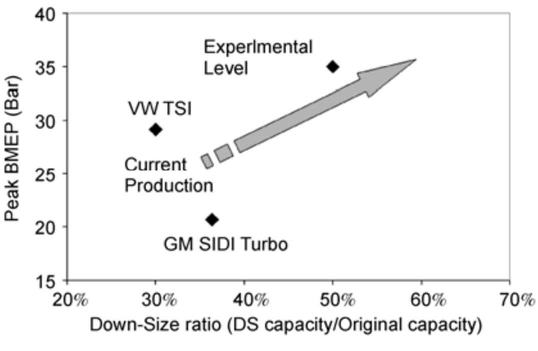

Figure 2 Advanced downsizing trend for gasoline engines.

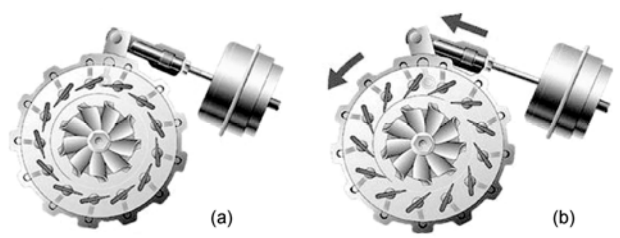

Figure 3 Variable Geometry Turbocharger turbine with pivoting nozzle mechanism in (a) closed positions at low engine powers for high exhaust energy recovery and (b) at open position when the engine power and exhaust flow are sufficient [6].

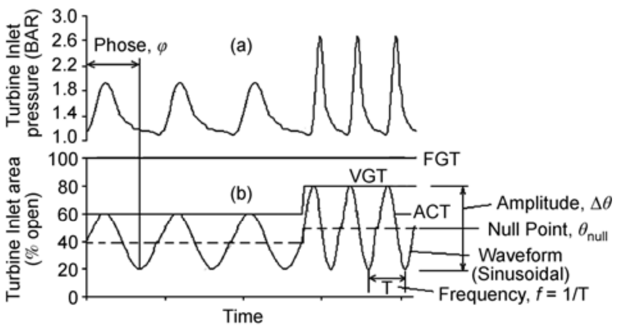

Figure 4 Comparison of the operating profile of a non-regulated turbine inlet area (FGT) to VGT and ACT turbine inlet area regulation schedules in (b), in response to a typical pressure profile (a) as it arrives at the turbine inlet from the exhaust valves [7].

The technology addresses, therefore, the fundamental problem of the poor generic engine-turbocharger match, since all current state of the art systems in turbocharging are still passive receivers of this highly dynamic flow without being able to provide optimum turbine inlet geometry through each exhaust gas pulse period.

3.1.3 Twin and double turbine scrolls

In order to maximize the energy of the exhaust driving the turbine, two turbocharger turbine entries are used in pulse turbocharging where twin or double turbine scrolls feed the highly pulsating exhaust flow directly into the turbine wheel. For the same turbine, tested with comparable double and twin entry housings, the former gave better efficiency at full admission but at partial admission the efficiency with the twin entry housing was significantly better. Using twin-entry radial inflow turbines in turbocharging systems gives the possibility to use the energy of pulsating exhaust gases (compared to a single entry turbine), and is very common practice (Figure 5).

3.1.4 Multi-Stage Turbocharging

Multi-stage turbocharging refers to any turbocharger installation that includes more than one turbine or compressor stage. There are several different combinations and the broad categorisation of multi-stage turbocharging is through a split in systems as a series or parallel and through the use of same-sized stages or small-big/high-pressure or low-pressure turbo/superchargers, respectively. A further categorisation is through continuous or sequential operation. The primary reason behind increasing the number of stages is to increase the boost level as a result of high engine boost requirement. When the stages are of the same size they are also, usually, in continuous operation (simple parallel, multi-stage system). The goal is here to provide sufficient boost for different groups of engine cylinders. When the stages are of different size these are usually connected in series so that the smaller (HP) turbocharger or supercharger can provide initial boost to cater for the transient response requirements of the engine. At high powers a combination of both HP/LP turbines and/or superchargers is in use to provide the full power requirement of the engine.

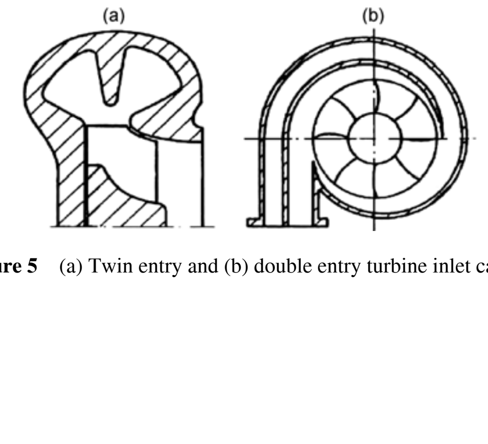

Figure 5 (a) Twin entry and (b) double entry turbine inlet casing.

Parallel, sequential systems are good for extending the flow range but do not deliver a higher boost pressure. These systems are ideal for passenger cars or turbocharging gasoline engines but are not appropriate for high output diesel engines. Series, sequential systems offer the benefits of both high boost pressure and wide flow range, mainly due to the fact that two compressors are used. Using two compressors replicates the effect of a variable compressor without the need for a complex mechanism in the compressor housing. The series, sequential system can have a high pressure turbocharger far smaller than that of a conventional two-stage system, improving transient performance by reducing the turbo lag that affects both driveability and emissions.

3.1.5 Turbocompounding

Beyond Euro VI, the probable legislated demand for improved fuel economy and CO_2 reduction will continue to drive waste heat recovery efforts. The concept of 'turbo compound', where a separate downstream turbine is used to recover exhaust energy and supply it back to the engine crankshaft, is well known. Introduced on heavy duty trucks by Scania in 1991, its subsequent implementation by other manufacturers has been sporadic. Rising BMEP levels and reducing EGR rates on heavy duty engines could increase the suitability of turbocompounding. Downsizing, combined with increasing BMEP would drive the need for smaller flow power turbines and hence increase the challenge of matching their higher speeds to the engine [4].

3.1.6 Electrification

A turbocharger with a motor/generator could be used for improved air delivery during a transient (i.e. transient assist) or power recovery. The transient assist particularly at the lower engine speeds and loads provides a significantly higher boost to the engine when needed compared to conventional, single-stage, mechanical turbochargers. The transient assist gives particulate reduction benefits on transient emission measurement cycles. For transient assist, the motor augments turbine power and for power recovery, the generator captures excess turbine power instead of typical flow bypassing. Figure 6 shows a number of electrical turbomachinery layouts that could be used.

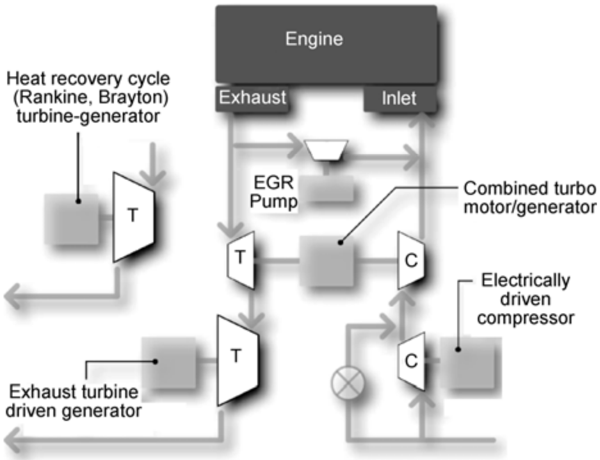

Figure 6 Potential electrical turbomachinery layouts [4].

A conventionally sized power turbine (around 50 kW for 13 L) could drive an electrical generator instead of a typical geartrain back to the engine crankshaft [5]. Separating the turbine speed from the engine speed gives potential for improved efficiency through design and operating speed flexibility. The physical separation of hardware could also offer useful packaging advantages as the power recovery turbine does not need to be in close proximity to the engine crankshaft as is the norm with current systems [4].

3.2 Compressor technologies

The boost pressure ratio of the turbocharger has to be increased to meet the requirement of constantly improved BMEP for vehicle engine downsizing. Figure 7 shows the boost pressure ratio needed to achieve certain BMEP of 2/4 strokes engines [8]. A boost pressure ratio of 4 is necessary to achieve a BMEP of 25 bar for a normal 4-stroke engine. High pressure ratio centrifugal compressors are keys to the improvement of boost levels.

3.2.1 Single Stage High Pressure Ratio Compressor

Wide compressor operating ranges are a challenge for a single stage compressor with high pressure ratio due to the transonic flow as well as the strong tip clearance flow. Although a pressure ratio as 4 or even higher, with good map width can be achieved by a carefully designed single stage compressor, stability improvement methods are widely adopted in the compressor for stability enhancement [9–12].

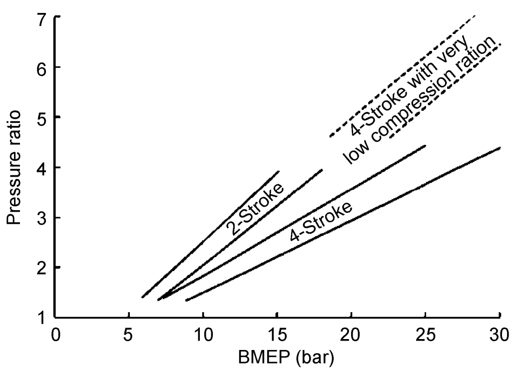

Figure 7 Required pressure ratio at different BMEP for 2/4 stroke engines.

Air injection at impeller inducer or diffuser inlet, and adjustable inlet guide vanes (IGV) are used for a centrifugal compressor stability enhancement. The compressor surge mass flow was remarkably reduced by these devices. A fluctuating plate at compressor outlet can be adopted for compressor stability enhancement. However, external energy input and devices are needed in those active methods.

Casing treatment near the inducer is the most widely used method of stability enhancement in a turbocharger compressor. Generally there are two types of topologies in the treatment, as shown in Figure 8. Usually the topology in Figure 8(b) doesn't work as well as the former because recycling flow via the slot downstream is blocked by inlet flow. Furthermore, it is confirmed that significant noise is raised in the topology due to the directly impact of inlet flow. The slot is also used at inlet of the vane-diffuser for stability enhancement in the centrifugal compressor. However, since a vaned diffuser is rarely adopted in vehicle turbocharger compressor due to the limitation on operating range, this passive method is hardly used in vehicle turbochargers.

Figure 9 shows a calculated, average static pressure distribution at the 90% blade height in a transonic centrifugal compressor near surge. As shown in the figure, the pressure increases continuity from the inlet to outlet of the impeller. Therefore, for the topology in sub-figure (b) (SRCT), the flow nearby is forced to recycle between two slots driven by pressure gradient. The recycling flow together with its pre-swirl effect can notably improve the relative inlet flow angle and alleviates the tip blade load. In order to derive the potential of SRCT on stability enhancement, SRCT with axis-asymmetrical configuration has been developed [13]. Figure 10 shows the tested pressure ratio of a transonic centrifugal compressor with and without SRCT. The surge line shifts towards smaller flow rates remarkably as a result of SRCT.

3.2.2 Multistage compressor

The multistage compressor (usually two-stage) which is

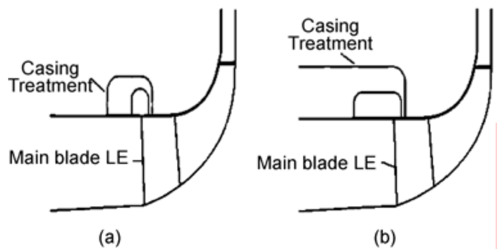

Figure 8 Two types of topologies casing treatment.

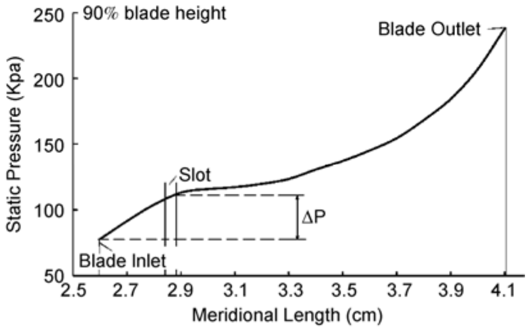

Figure 9 Averaged static pressure along the meridional length of passage.

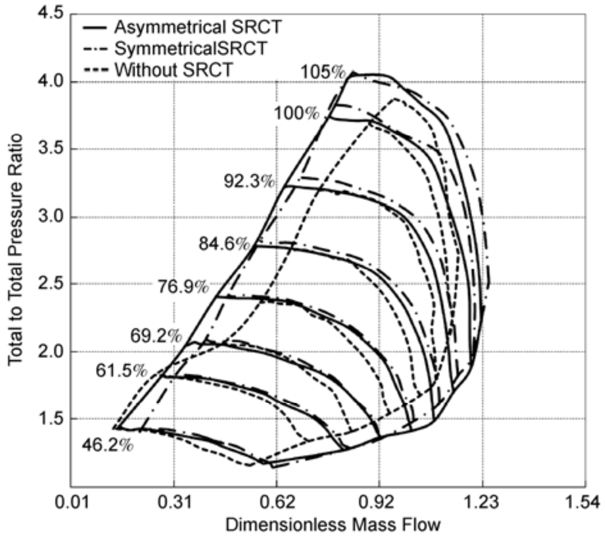

Figure 10 Measured performance comparison of compressors with/without SRCT.

connected on a common shaft with a turbine has been developed to achieve high boost pressure while keeping low rotational speed which is beneficial in terms of stress reduction and efficiency as well as operating range. Figure 11 shows three types of two-stage compressors, which are the back to nose, back to back two-stage centrifugal compressor arrangements and the axial-radial compressor. The first two types can achieve higher boost pressure than the third type

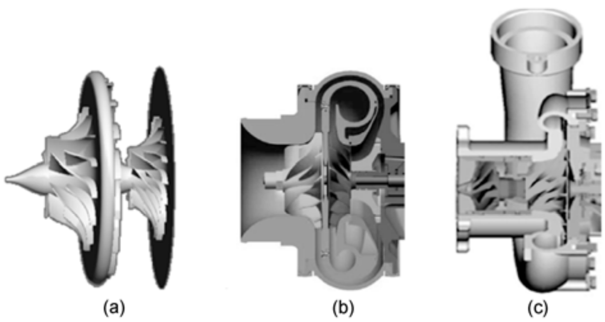

Figure 11 Different types of multistage compressors [14, 15]. (a) Back to Nose; (b) Back to Back; (c) Axial-Radial.

due to the two-stage centrifugal compressor. However, the axial-radial configuration is more compact.

Although higher boost pressure can be easily achieved by multistage compression, the matching between two compressors is difficult—an issue closely related to the operating range and efficiency of the whole turbocharger. Furthermore, additional energy should be extracted by the single turbine to drive the two compressors.

4 Boosting systems

Boosting systems today, in accordance to their level of availability can be classified as Available or Under-development. Underdevelopment systems cover the range from laboratory demonstrators to near production systems.

4.1 Available systems

4.1.1 Single Stage Turbocharger

Fixed Geometry Turbochargers (FGTs) equipped with a wastegate are the reference in turbocharger development and were developed purely in order to take advantage of the energy lost during the exhaust process of an internal combustion engine.

4.1.2 Single Stage Supercharger

Despite the existence of two main categories of mechanical superchargers (rotodynamic and positive displacement), it is the conventional single stage, centrifugal superchargers which are in predominant use today in internal combustion engines. The supercharger is a compressor typically driven directly from the engine's crankshaft via a belt or gear drive.

Today superchargers have been used in a number of passenger vehicle applications but not in diesels. In addition, in downsized efforts so far, single stage conventional supercharger (or wastegated turbochargers for that matter) offers no solution as the boost pressure that can be developed is insufficient. More complex or advanced solutions exist which are analysed in a following section.

4.1.3 Variable Geometry Turbocharger

As it is known, the range of operation of a modern turbocharged engine is very broad and FGTs are designed to recover the emitted exhaust energy most efficiently in a narrow range of engine operating conditions. Outside of this narrow range the FGT exhaust energy recovery suffers substantially. VGTs address this deficiency to an extent by adjusting turbocharger geometry to the dynamics of the flow particularly at the lower end of the engine operating range in an attempt to preserve the kinetic energy of the exhaust gas stream regardless of the amount emitted (Figure 3). VGTs have been very successful in this respect but still do not account for the highly dynamic nature of the energy encapsulated in individual fluctuations during each individual engine exhaust cycle.

4.1.4 Multistage Turbocharging

Multistage turbocharging is a generic term used to describe the installation of two or more turbines and/or compressors to boost a single engine installation. It is an industry accepted technology and already in production. This technology has excellent transient response and it is capable of meeting the needs of current and future downsizing options. The variations of such installations are numerous and there is an issue with the nomenclature used by various OEMs which are explained below:

4.1.5 Parallel Multi-Stage

In parallel turbocharging, identically-sized turbochargers are used, each fed by a separate set of exhaust streams from the engine. The split in the exhaust manifold encapsulates the sequential firing of each group of cylinders which is optimal in this respect, to the maintenance of satisfactory levels of exhaust pulsating energy supply to the turbocharger [5]. Typically, two or three cylinders of a sequential firing order are placed under the same manifold, which drives their exhaust gases to one turbine. In this respect, parallel turbocharging includes twin turbochargers each of which is feeding a bank of two or three cylinders. In cases of more than 6 or 8 cylinders three or more identical turbochargers can be used.

For our purposes here, if the compression of air is not carried out in series, but independently, the turbines are connected to only part of the engine cylinder number and the boost air is mixed further downstream, this system is classified as a parallel turbocharging system (regardless of the turbine arrangements involved).

4.1.6 Series Multi-Stage

Conventional two-stage turbocharging employs two turbochargers working in series at all times. Two turbochargers are used in series, with the exhaust gas feeding through both turbines and the air being pressurised by either a small (high pressure, HP) or large (low pressure, LP) compressor depending on the operating point of the engine.

Conventional two-stage systems are good for extending the flow range but do not deliver a higher boost pressure. These systems work well for gasoline passenger cars of today but are not appropriate for future very high boost gasoline engines or high output diesel engines.

4.1.7 Parallel/Series Sequential Turbocharging

In this case two turbochargers are used in sequence, with the exhaust gas feeding through both turbines. At low speeds the smaller turbocharger is in operation. As soon as the engine speed/load combination increases the mass of exhaust gases passing through the smaller turbocharger, a signal is given to a bypass valve to allow operation of the larger capacity turbocharger to take over the engine's boosting requirements.

Sequential turbochargers can be laid out in *Parallel* and *Series* configurations using the same HP/LP components, except in the parallel sequential case (Figure 12), the output of both compressors is merged from two separate compressor outlets into the intake manifold, whereas in the series sequential case (Figure 13) the output of the HP compressor is fed into the LP compressor.

Sequential systems offer the benefits of both high boost pressure and wide flow range, mainly due to the fact that two compressors are used. Using two compressors replicates the effect of a variable compressor without the need for a complex mechanism in the compressor housing. The modulated two-stage system can have a high pressure turbocharger far smaller than that of a conventional two-stage system, improving transient performance by reducing the turbo lag that affects both driveability and emissions.

4.1.8 Twincharger

A variation of multistage turbocharging which merits differentiation is the so called "twincharger" (not to be confused with "superturbocharger" systems under development, analysed in the following section). This refers to a combined supercharger-turbocharger system used on some gasoline engines today. The combination of a turbocharger and a supercharger mitigates the weaknesses of each other (Figure 14). The supercharger offers exceptional response (lag-free) and high torque at lower engine speeds and increased power at the higher end of the speed range. Twincharging is, therefore, attractive for downsized engines, especially those with a large operating speed range, since they can take advantage of a broad torque band over a large speed range.

4.1.9 Turbocompounding

Although the use of turbocompounding is relatively new for

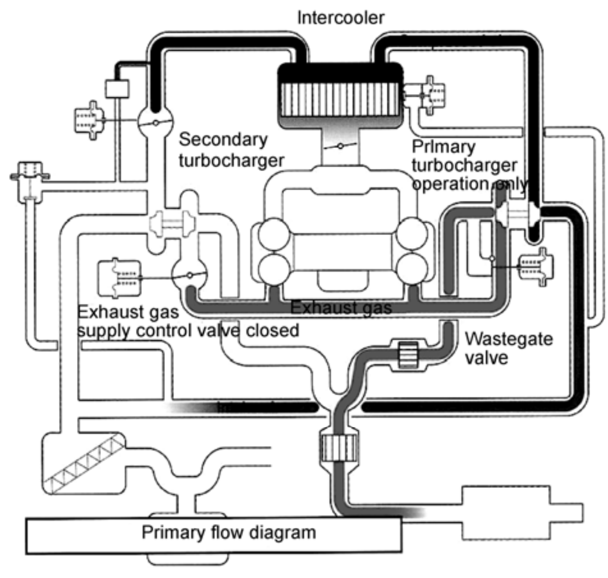

Figure 12 Parallel sequential turbocharger installation.

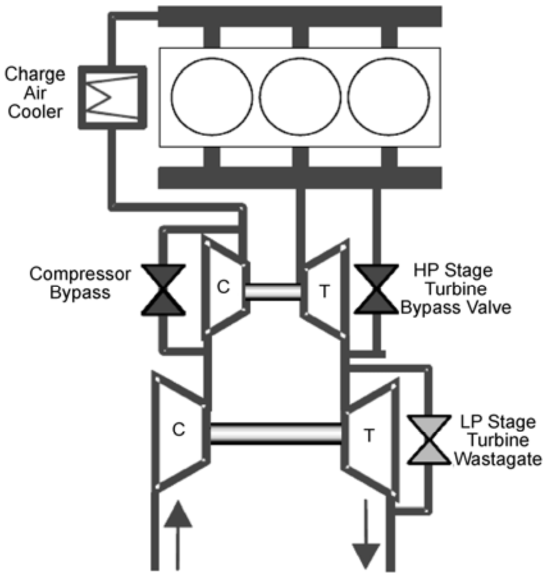

Figure 13 Series sequential turbocharger installation [4].

diesel truck applications, the concept actually goes back quite a long time. The concept was originally used back in the late 1940s and '50s on two notable aircraft engines, the Wright Cyclone and the Napier Nomad, although its promise of low fuel consumption for transport aircraft was soon overtaken by the rapid development of the gas turbine and the turboprop engines.

In the case of automotive diesel engines, turbocompounding means the introduction of a power turbine downstream of the turbocharger. The power turbine generates more work re-using the exhaust gases from the original turbocharger. The work generated by the power turbine is then fed back into the engine crankshaft via a sophisticated transmission. It differs from a standard turbo as it does not have a compressor cover or compressor wheel. Instead it uses a gear connected to the turbine shaft, Figure 15.

The advantages of the installation are due to the extraction of work from waste energy, causing the overall thermal efficiency of the engine to increase. In simple terms more is extracted for the same amount of fuel consumed. This creates a more powerful engine and provides better efficiency.

The first commercial application of this type of turbocharging occurred in 1993.

4.2 Systems under development

In this section boosting systems under development are presented. These are at least relatively new with minimal or non-existent market uptake yet.

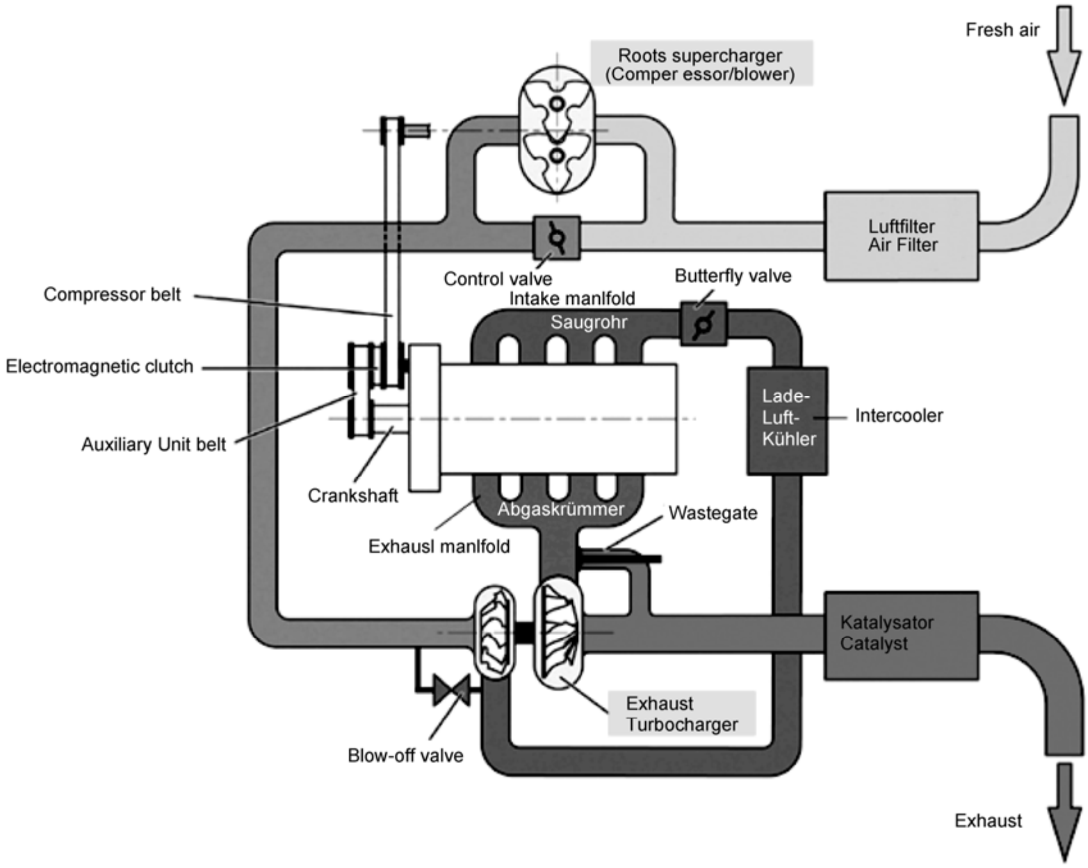

Figure 14 Example of a (series) twincharger installation.

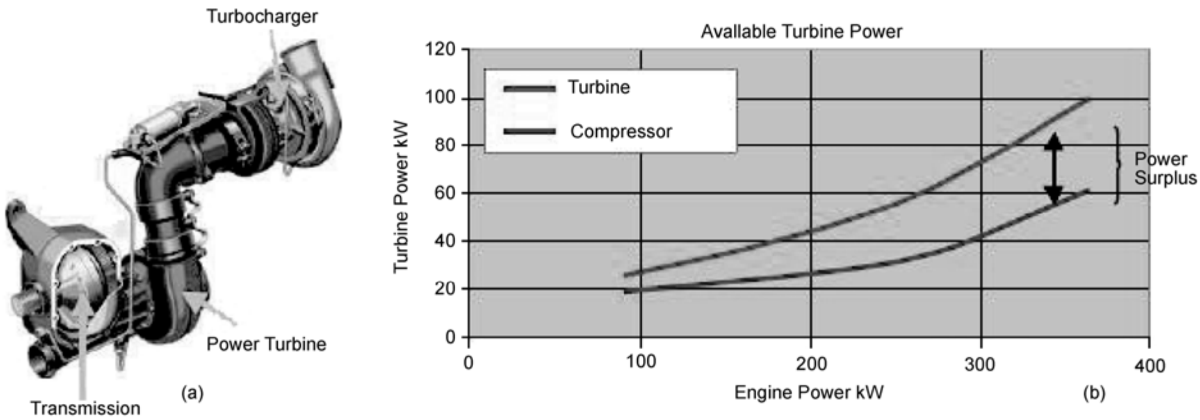

Figure 15 (a) Typical mechanical turbocompounding installation and (b) power surplus chart which is capitalised upon by the turbocompound installation, Hopmann, 2002 [16]

4.2.1 Electric Turbocharger

An electrically assisted turbocharger (sometimes referred to as a hybrid turbocharger) is a turbocharger fitted with an electric motor/generator around the turbocharger shaft and bearing housing and between the compressor and turbine housings (Figure 16). The electric motor/generator is the turbocharger power assist system and is a device capable of bi-directional energy transfer to the turbocharger shaft and energy storage. When applied to turbocharged engines, this power assist system results in a significant reduction of turbo-lag [17]. The electric motors used are typically induction or permanent magnet motors.

The specific advantages brought by electrically assisted turbochargers are worthy of investigation [18], because they can increase boost pressure at low engine speeds (thus eliminating turbo-lag), maintain turbocharger speed during gearshifts, reduce turbocharger speed under high engine power conditions and also recover exhaust energy.

4.2.2 Electric Supercharger

The electric (hybrid) supercharger is a very similar device to the turbocharger with the omission of the power turbine. In its latest development it features a variable torque enhancement system (VTES) and features an air cooled switched reluctance machine, coupled to electronics and an optimized radial compressor, delivering high airflow, pressure and efficiency (Figure 17).

The technology has already been demonstrated at the experimental level on an engine. The electrical operation can be easier to integrate on an engine but at a higher cost.

VTES is optimized to use the standard 12V vehicle architecture. The system can be applied to new or existing vehicles much more rapidly and at lower cost and investment than competitive solutions.

4.2.3 Superturbocharging

Referred to in recent literature as “superturbos” this is a combination (electrified or mechanical) of turbochargers and/or superchargers which may also be capable of turbocompounding at the same time. Several such models are in various stages of development, proof of concept or further. The two principal versions (electrical/mechanical) are:

(1) TurboSuperGenerator. The turbosupergenerator (TSG) combines supercharging and hybridisation advantages with the additional benefits of multi-stage turbocharging. It allows electrical supercharging as well as elec-

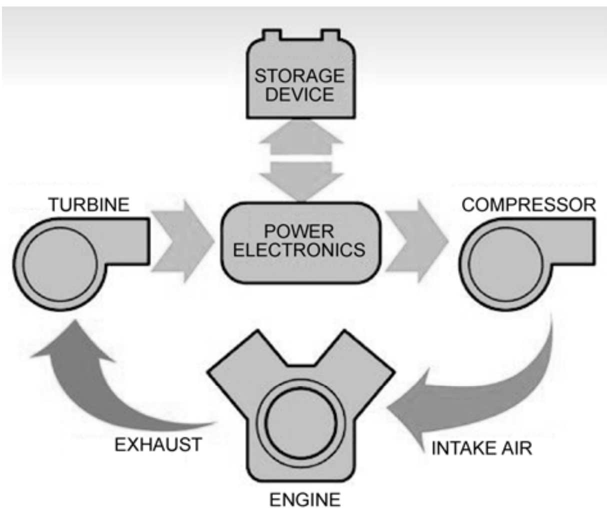

Figure 16 Electric (Hybrid) Turbocharger [19]

Figure 17 Electric (Hybrid) Supercharger [20]

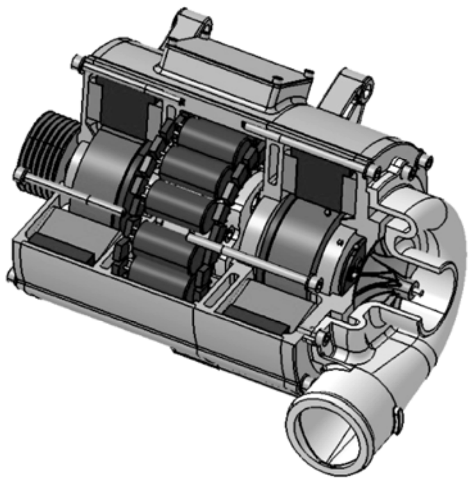

Figure 18 Electric (Hybrid) Supercharger [21]

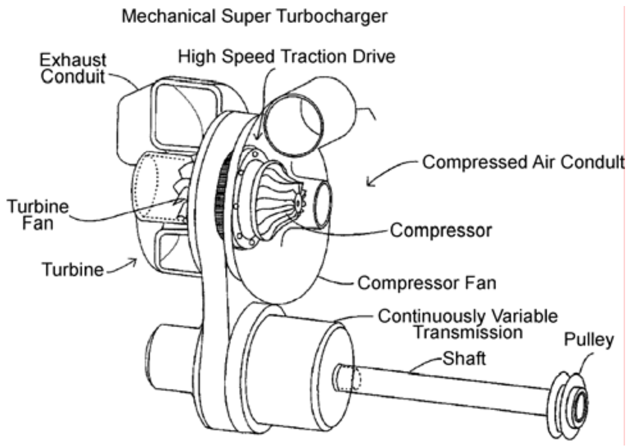

Figure 19 Mechanical SuperTurbocharger [22].

trical generation to replace the alternator of the engine. TSG is fundamentally different from other super-turbo systems in that the supercharger is installed between a conventional low-pressure turbocharger and the engine—in effect the supercharger-generator is the high-pressure compressor stage and only the LP-turbocharger operates in the exhaust system (Figure 18). When coupled to a turbocharger, it can also produce turbo-compounding operation. It incorporates a traction that sits on the compressor side and hence it sees a much reduced heat loading as it is far away from the exhaust. Key testing is not yet available to confirm the performance, reliability and durability.

(2) Mechanical Superturbocharger. The Mechanical Superturbocharger (MSG) is an enabling technology for engine downsizing without loss of vehicle transient response and peak power. The technology combines the benefits of turbocharging, supercharging and turbocompounding using two unidirectional modes of mechanical energy transmission. The first method boosts engine power via turbocompounding and the second transfers power from the engine to a supercharger to boost transient response at lower speeds. The main elements of the technology are a traction drive, compressor and turbine all being attached to a single crankshaft and subsequently connected to a CVT (Figure 19).

4.2.4 *Electric Turbocompounding*

Electric turbocompounding refers to a system that converts waste exhaust energy to shaft work, using a turbine, and couples it back to the engine electrically. When exhaust gas passes through the turbine, the pressure and temperature drop as energy is extracted and due to losses. The power taken from the exhaust gases is about double compared to a typical turbocharged diesel engine. To make this possible the pressure in the exhaust manifold has to be higher. This increases the pumping work from the pistons. The net power increase with a turbo-compound system is therefore about half the power from the second turbine. For a 10% power increase, there is a 5% efficiency improvement. The higher pressure in the exhaust manifold results in slightly more of the exhaust gases being trapped in the cylinder during scavenging. This can be seen as a kind of internal EGR [23]. A schematic of the system can be seen in Figure 20.

4.2.5 *Blade Supercharger*

The Blade Supercharger is a positive displacement compressor that can be used for both petrol and diesel engines with the ability to meet the boost requirements of downsized engines. It is able to change boost pressure without changing rotational speed. The compressor is designed for high volumetric and thermal efficiency, and the geometry of the compressor allows high efficiency heat recovery. It is oil free, and other features include small size, low vibration and quiet operation (Figure 21).

The supercharger uses a variable port design which allows for a real time variation of mass-flow and internal compression ratio. A key feature is the compressor's ability to vary flow and pressure with minimal efficiency loss, without the use of Variable Speed Drive. It is a rotary device with a wrapped toroidal chamber. The key features are

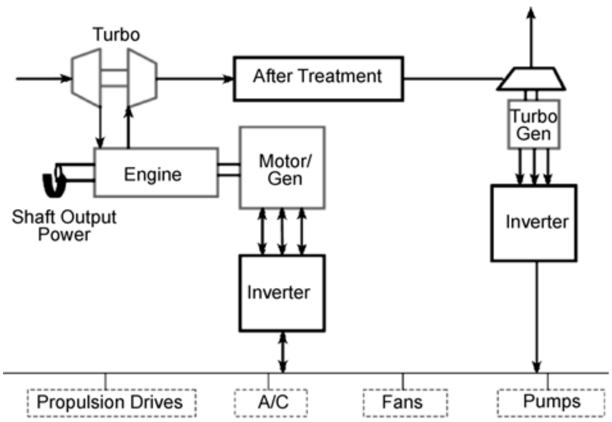

Figure 20 Electric Turbocompound installation [24].

Figure 21 The Blade Supercharger [25].

a rotating blade, which passes through a slot in a rotating disc once per cycle. The unit is therefore a compact, double acting rotary compressor.

4.2.6 Active Control Turbocharger

The Active Control Turbocharger is a novel type of turbocharger aimed at improving the turbocharging of internal combustion engines. Additional energy is extracted from the engine exhaust by an innovative technique that considers the fluctuations in exhaust pressure over small time periods (Figure 4). The system increases the available power from the turbo charged engine by up to 20% compared to the current state-of-the-art VGT. In addition, the use of ACT produces a gain in thermal efficiency of the engine compared to VGTs as more energy is extracted from the engine exhaust, which in turn increases the useable energy which can be obtained from a given mass of fuel. The main difference of the two systems which are outwardly almost identical is a more powerful actuator and associated increase in the power supply and control required, compared to a VGT.

5 Assessment of boosting options

The level of boosting achievable by available and under-development systems can be quantified by establishing a baseline for comparison:

Gasoline - as already mentioned, most gasoline engines are still single stage FGTs and with approximately three-quarters of the gasoline engine output being of the naturally aspirated (N/A) variety, then any downsizing efforts through the adoption of any of the boosting systems discussed will have to be assessed against this N/A baseline.

Diesel - in the diesel market on the contrary, two-thirds of the market (in Europe) is VGT-equipped with the rest of the production output being primarily single stage FGTs and to a much smaller extent, two-stage and turbocompounds. Naturally, any downsizing efforts in the diesel market will have to be compared against the primary technology in use in diesel engines today: VGT.

From Figure 22, it may be broadly stated that single stage systems are at their limit as an option for the provision of the level of boost required of future downsized engines. In this figure various types of gasoline and diesel turbocharged version are illustrated, both single and two-stage.

It is obvious from Figure 22 that two-stage turbocharger systems are more capable in both peak, specific torque and peak, specific power than any combination of single stage turbocharger, regardless of cam phasing, injection system or number of turbine entries (scrolls). Another conclusion from Figure 22 is that gasoline engines even with simpler boosting systems offer a higher specific power output thus enhancing the statement in the introduction of this paper about the greater scope for downsizing offered by gasoline engines. In addition, in terms of comparative bases, the range of improvement of current and future boosting systems spans from the category “Base Engines” to the category “Gasoline 2-Stage” for the present gasoline envelope and from the category “Diesel VGT” to the category “Diesel 2-Stage” for diesel engines.

Depending on application the slope of the development

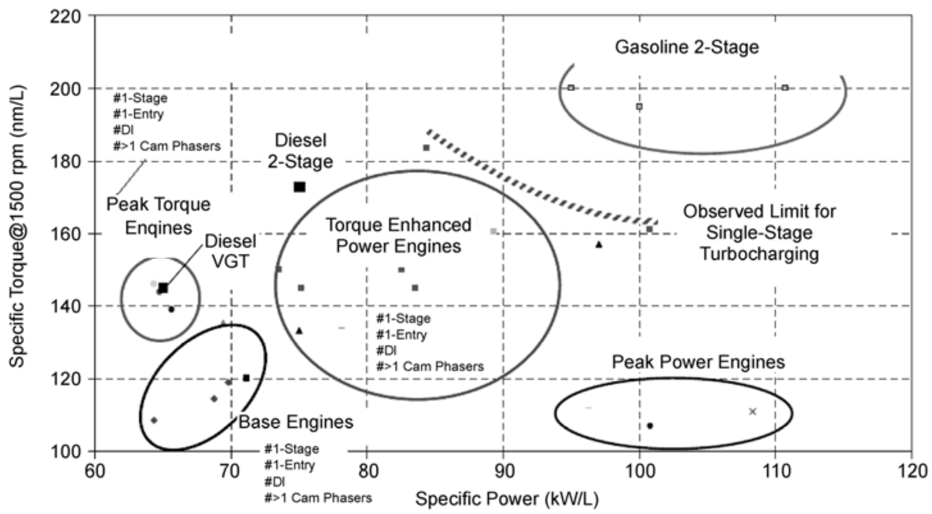

Figure 22 Gasoline and Diesel turbocharged engine specific torque and specific power performance with boundary of single to two-stage cross over for gasoline [26].

line joining each respective category of gasoline and diesel will have to vary, as other applications require higher specific torques (heavy duty diesels at extreme conditions, for example) or higher specific powers (for extreme gasoline engine downsizing, for example).

Further to the scope of single versus two-stage comparison, Figure 23 illustrates the relative BMEP performance over the engine speed range for a gasoline engine with a single stage FGT with a wastegate (WG), a VGT and a two-stage system. The superiority of the two-stage system is significant throughout the speed range, which also translates to a faster transient response and vehicle acceleration [26].

The level of specific torque in Figure 22 suggests a BMEP level for one litre of swept volume of 25 bar, which is what is indicated in Figure 23 (2-stage turbocharger line). In terms of diesel performance, the mandatory EGR rate increase will require ever increasing BMEP levels and a nominal cut-off line is indicated in Figure 22.

From Figure 22, the specific torque levels for the range of modern (light-medium duty) diesels are in the range of 140Nm/l (VGT level) to approximately 175Nm/l (2-stage turbocharger level). This equals a BMEP range for typical diesels of today of between 18 bar and 22 bar [4].

The large scale upward BMEP shift from 22 bar for Diesel and 25 bar for gasoline necessitates a compressor pressure ratio greater than 4:1 for diesels and at least a similar pressure ratio for gasolines. In addition, the turbine exhaust flow range needs to be variable and of at least similar ratio as the compressor range [4].

A Six Sigma QFD methodology provides scoring for a number of turbocharger systems [4] but covers a generic template and is not specific to downsizing options. According to this table the VGT is the single most capable turbocharger (including a number of hybrid boosting options under development), while the least favourable option is the mechanical turbocompounding option. In terms of downsizing, several different factors can be assessed. A primary categorisation can be made in terms of delivery of the required boost levels; the second is the generic factor for a turbo/supercharger installation of delivering on engine fuel efficiency; the third is cost and the final requirement is compactness.

In Figure 24, the available boosting system percentage increase in thermal efficiency terms in comparison to a naturally-aspirated (N/A) baseline is provided. Sequential (Series/Parallel, SST/PST), twincharger and series multi stages (two-stage, typically) offer the highest gains and are already favourite in several downsizing efforts of recent years. In terms of single-stage systems, VGT is the only clear option, if relatively limited in terms of boost level scope.

In addition, and with respect to the attainment of future boost level attainment, it may be stated that the five systems at the left of Figure 24, are all single staged systems and, therefore, subject to single stage pressure ratio limitations such as those illustrated in Figure 22.

Figure 25, on the other hand, offers the same percentage increase in thermal efficiency in comparison to an N/A baseline for all under-development systems described in the previous section. It needs to be noted, beforehand, that the performance levels indicated reflect in many cases the estimated or modelling results and are not the outcome of experimental testing.

Here, the situation is not as clear except to say that many of the under-development systems offer similar levels of

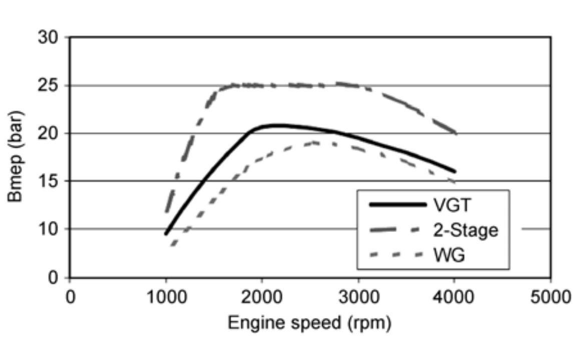

Figure 23 Bmep achievable with BorgWarner series sequential turbocharger, VGT and a standard fixed geometry turbocharger with a wastegate (WG) [26].

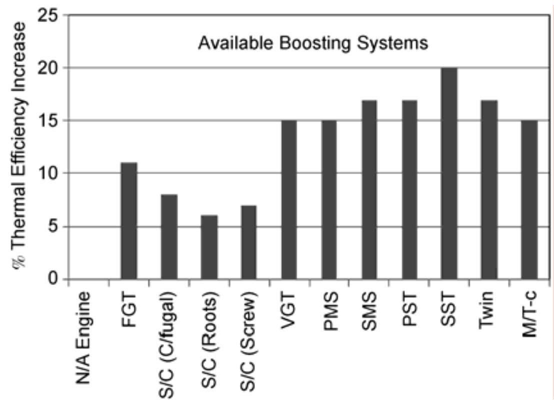

Figure 24 Increase in thermal efficiency of available boosting systems compared to N/A baseline.

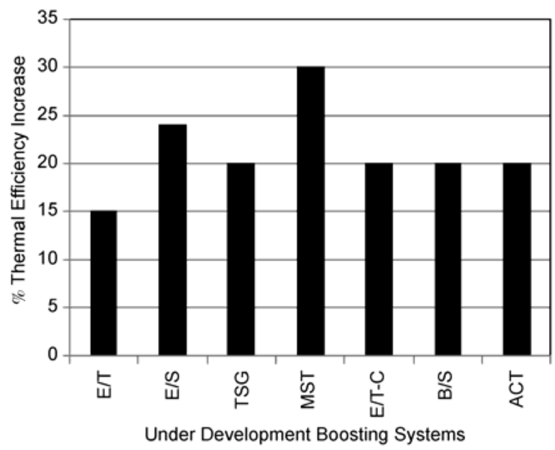

Figure 25 Increase in thermal efficiency of under-development boosting systems compared to the same N/A baseline as in Figure 24.

improvement. One boosting system offers a clear case of higher overall improvement of 30% (the mechanical superturbo), with the electrical supercharger (VTES) offering a second best performance, while the equivalent electric turbocharger offers the least improvement (in connection to the increased level of inertia of the combined turbine and supercharger rotating assembly). Even though the electric turbocharger (E/T), the electric supercharger (E/S), the blade supercharger (B/S) are single stage systems, the performance levels attained are not commensurate with the existence of more than one stage in the compressor or turbine (as is the case with available boosting systems).

No direct conclusion can, therefore, be drawn with respect to the effect of single or multi-stages. Obviously the high level of hybridisation, the existence of CVTs, traction drives or totally different design on principle offer very different performance propositions, compared to today's production boosting systems. It is still clear, however, that the advantage in the first category of interest (boosting level attainment) resides with the multi-stage systems or those offering waste heat recovery capabilities.

Figure 26 illustrates the packaging constraints as a percentage of total powerpack volume. The baseline is again the N/A engine and the percentage increase in space required of the different, available boosting systems is illustrated. As expected, the space requirement of two-stage systems is approximately double of the single-stage systems, with the parallel sequential system being the highest. Significantly, the VGT system—the most capable of today's single-stage boosting systems—offers the second smallest space requirement for a powerpack boosting system.

Figure 27, indicates the equivalent space requirements for under-development boosting systems. Again the significantly smaller space requirements of single-stage systems are evident (E/T, E/S, B/S and ACT).

Overall, these new boosting systems have a higher space requirement than the space requirement of today's systems as a result of larger actuators and power electronics (ACT), the installation of motor generators (E/T, E/S, TSG and E/T-C) and the inclusion of further mechanical transmission and traction systems (MST). This increase is more than offset by the significant efficiency benefit offered by these systems.

The ever increasing number of boosting system options is broadly covered in this and the previous sections. The number of actual systems that have been realised or that offer themselves for further development is even greater. A significant scope for further development may be found in the combination of available and under development boosting systems:

- Dual Compressor VGT (2-stage compressor on the same shaft to a single VGT turbine);
- Two-stage with a VGT high pressure stage (instead of a standard FGT);
- Twin entry VGT.

6 Conclusions

Downsizing is a an established technical solution in diesel engine and a relatively recently adopted solution for the improvement of gasoline engine efficiency, that is, at the time of writing, established as the most significant emissions reduction tool in the design of modern gasoline and diesel engines. The choice of boosting system for the OEM is becoming increasingly difficult due to the large variety of systems available or under development.

There is greater scope for downsizing offered by gasoline engines than diesel. However, both engine types will benefit. BMEP levels for gasolines of at least 30 bar by 2020 at the latest is expected to be the norm (25 bar in the short term) from approximately 22 bar which is the highest level achieved today. Diesel engine BMEP is also set to rise from approximately 25 bar today. The question of reliable operation remains, however and a complementary number of

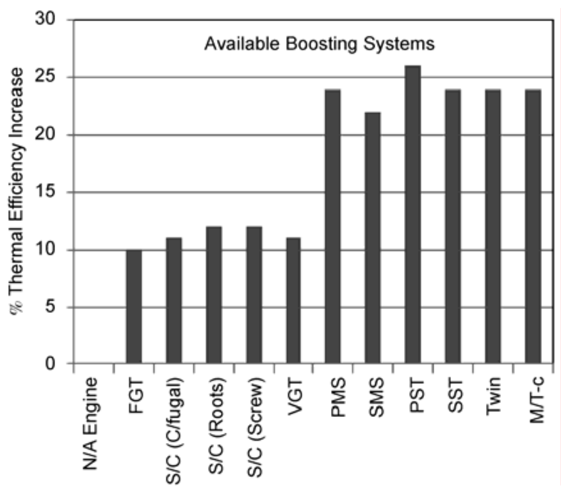

Figure 26 Increase in packaging requirement due to available boosting system installation compared to N/A baseline.

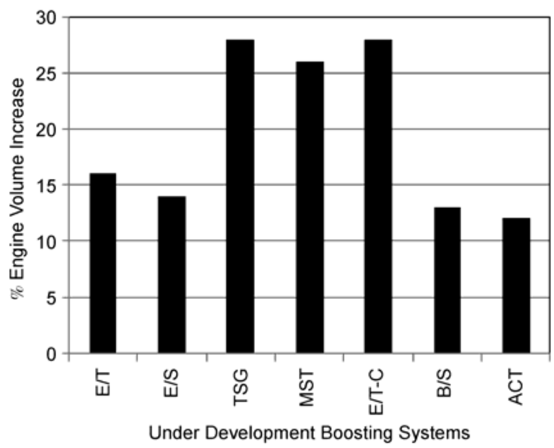

Figure 27 Increase in packaging requirement due to under-development boosting system installation compared to N/A baseline of Figure 26.

technologies such as those mentioned in the Introduction will be required.

Single stage compressors cannot deliver the boosting levels required for the downsizing needs of the future especially after the short term engine trend (from today to 2015).

The resurrection of turbocompounding will play an increasingly important role as a downsizing option not only in its developed, mechanical form but also increasingly in hybridized forms.

Hybridisation will continue to be developed to play increasing roles as a truly novel reality in turbocharging and generally as a boosting system enabler. As with turbocompounding a key challenge is the under-hood space requirement of these new systems but even more importantly for hybridised system the primary challenge will be cost effective operation.

Other options such as alternative supercharger or advanced turbochargers (ACT) designs will offer significant benefits at much reduced costs compared to hybridisation and probably even mechanical turbocompounding.

In addition, significant breadth of scope exists in combining existing or under development technologies. The way forward in boosting systems seems to revolve to a significant degree around the re-usability of past boosting system knowledge and existing systems which combined with other existing or developing technologies can deliver solutions for the future. With so many systems available or about to become so, and with, in many cases, similar performance levels, individual applications will have to be carefully studied before selection of the appropriate system is made.

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