TURBOCHARGING OF IC ENGINES: AN OVERVIEW OF THE HISTORY, CURRENT STATE, AND THE DEVELOPMENT TRENDS

Dobrivoje Ninković[1], PhD

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INTRODUCTION

The advantages of filling the IC engine cylinders with air by using a compressing device of arbitrary design in comparison to their counterparts with air suction were recognized very early in the engine development. It is known that late in the 19th century both Gottlieb Daimler and Rudolf Diesel worked on concepts for forced cylinder induction by mechanically driven devices.

In 1905, Swiss engineer A. Büchi applied for a patent on a method for utilizing the exhaust energy of an IC engine for driving a turbine attached to the crankshaft of the same engine, creating thus the so-called compound engine. However, there was also a centrifugal compressor on the crankshaft, the purpose of which was to supply the engine with compressed air, increasing thus the engine specific power. This patent is generally seen as the generic one for the introduction of forced cylinder induction, i.e. charging with air, whereby the compressor is driven by a turbine that in its turn extracts the energy from the engine exhaust gases. For obvious reasons, this technology is referred to as turbocharging.

A similar method of forced cylinder induction whereby a centrifugal compressor is driven by mechanical means, such as e.g. the engine crankshaft, is commonly termed super-charging. This technology found wide¬spread use in the field of aircraft IC engines, especially in the period before and during the World War II. A great majority of aircraft engines of that time were equipped with sophisticated supercharging systems, usually driven by variable-speed drives.

However, turbocharging represents nowadays the prevalent method for forced cylinder induction practically in all IC engine sectors. It is seen as a prime means for increasing the power density of IC engines, which in turn results in reduced CO2 production. Although the former has always been the goal of turbocharging in the large engine sector, it is in conjunction with the intensifying application of this technology to road vehicle engines that a new term was coined, referred to as "downsizing". It is taken to mean improving the power and torque output of the engine while reducing its size, whereby the inevitable performance loss thus incurred is compen-sated by increased use of turbocharging.

Turbocharging is also instrumental in meeting the ever-stricter emission requirements posed to the engine manufacturers by the legislation bodies, since downsizing and emission reduc¬tion often represent conflicting requirements.

It is also mainly due to turbocharging that modern IC engines are to be found amongst the most efficient thermal machinery in general. For example, modern slow-running two-stroke Diesel engines attain efficiencies of 55%, and the newest generator sets driven by four-stroke gas engines with two-stage turbocharging reach an efficiency figure in excess of 46% referred to the electrical output [1].

The term two-stage turbocharging can refer both to series and parallel connections of two indivi¬dual turbochargers. The former is employed in order to obtain boost pressures

1 Dobrivoje Ninković, Dr. Tech. Sci., Ruchwiesenstr. 28, 8404 Winterthur, Switzerland, email: dninkovic@bluewin.ch

higher than the ones possible with a single compressor, whereas the latter is used when a larger mass flow rate is needed at the same boost pressure. In this paper, this term will be used exclusively to refer to a series connection of two turbochargers.

MAIN REASONS FOR THE INCREASING SIGNIFICANCE OF TURBOCHARGING

Analyzing the history of turbocharging, it is possible to speak of two time periods in which the development and application have been located in two different IC engine segments, whereby the main driving forces were not quite the same. The beginning of the first one is located at the start of the past century, coinciding roughly with the first patents relating to turbo-charging. The field of application consisted mainly of large four-stroke Diesel engines, at first for ship propulsion, and later also for locomotives [2]. The reason for investing into the new techno-logy was that a turbocharged engine became by this means able to deliver more power than its naturally aspirated counterpart of the same size. This meant more room for the cargo, which was well understood by the ship owners, generating thus the demand for such engines, and driving the research and development. The production of turbochargers took place on the one-off basis, requiring close cooperation between the engine and turbocharger manufacturers [3].

The second period of intensive turbocharging technology development started some 25 years ago in the small IC engine sector. Customarily, the latter is taken to mean engines used on vehicles for road transportation, i.e. on trucks, buses, and passenger cars. The development pace has been very fast, resulting in practically all modern Diesel engines produced today being equipped with sophisticated turbocharging systems, whereas engines even with simple turbochargers were a minority only twenty years ago.

This trend has been brought about by the exhaust gas legislation in the developed countries, which started at the beginning of the seventies of the last century by limiting the carbon monoxide (CO) for Otto engines and smoke and sulphur oxide ($SO2$) emissions for Diesel engines, and culminating in the UNECE Convention of 1979 [4]. While the engine manufacturers were able to meet the ever stricter CO and HCx emission norms for Otto engines by a combination of catalytic exhaust gas converters, closed loop engine control, and engine design changes, it was the Kyoto Protocol of 1993 regarding the emissions of carbon dioxide ($CO2$) that posed a new challenge to the entire road transportation industry. Limiting the $CO2$ emissions means reducing the fuel consumption, and this can not be achieved by the exhaust gas treatment methods only.

Referring to Fig. 1 below, between 2005 and today $CO2$ emissions of newly produced vehicles were either reduced or requested to be reduced at annual rates between 2 and 4.8%. The technology that helped achieve most of these results has been the downsizing, as already mentioned in the Introduction.

According to the above diagram, the $CO2$ emission values of 2015 will have to be reduced by 50% in the next ten years, which in combination with the simultaneous reduction of other pollution gases constitutes a radical requirement that calls for further development of the downsizing, of which turbocharging is an inseparable part.

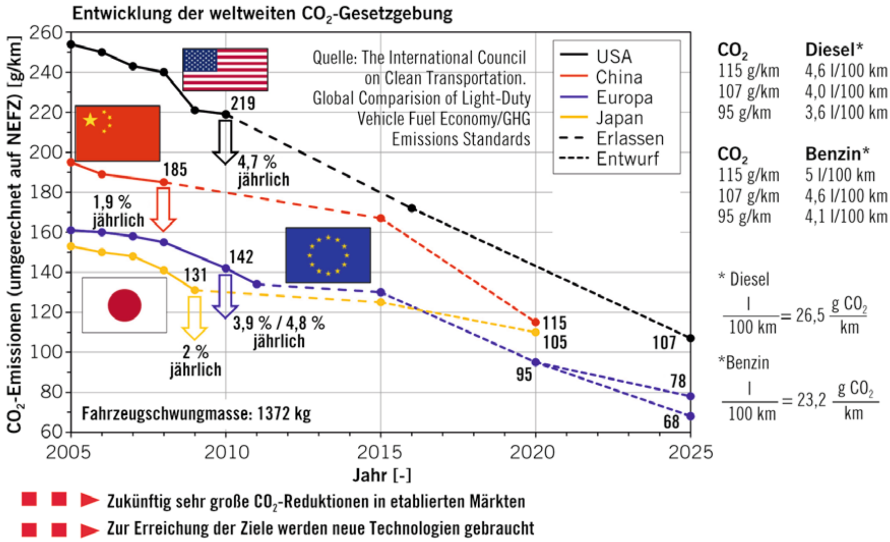

Figure 1. The CO2 emission legislation worldwide [5]

The above two periods in the development of the turbocharging technology are not sharply divided between the large and small engine sectors. For example, Swiss company Saurer (now Iveco) started series production of turbocharged Diesel engines for trucks and buses in 1938, the reason being power loss in naturally aspirated engines at high altitudes in Swiss Alps. A large number of turbochargers were built in the U.S.A. for aircraft engines in the Second World War, again in order to compensate for the power loss at high altitudes.

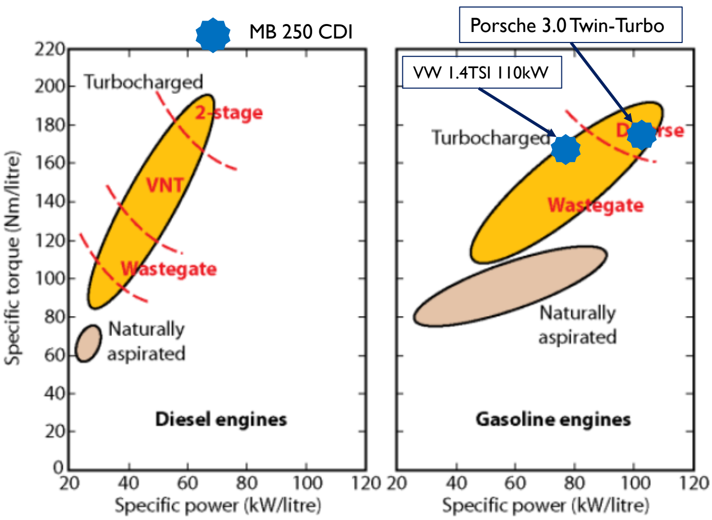

Figure 2. Comparison of naturally aspirated and turbocharged road transport engines [6]

Turbocharging modifies both the torque and power delivery characteristics of downsized engines. A comparison of naturally aspirated Diesel and gasoline engines with their turbocharged counterparts of Fig. 2 above shows a trend toward higher torque densities in the Diesel engine case and higher power densities in the gasoline engine case. The new data (MB 250CDI, VW 1.4TSI 110kW, and Porsche 3.0 Twin-Turbo) augmenting the ones published by Baines in 2013 [6], makes it apparent that these trends continue with modern engines.

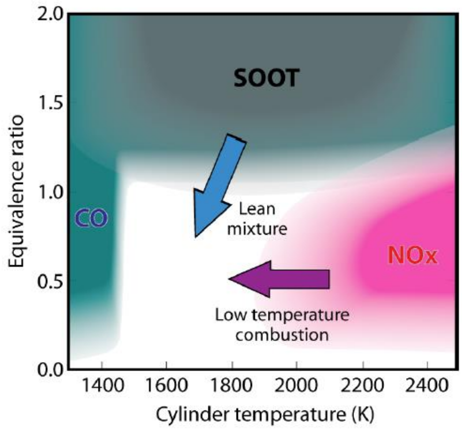

Figure 3. Clean combustion requirements [6]

Reduction of the emissions of polluting gases is the second area where turbocharging contributes in achieving the legislation targets. As the illustration in Fig. 3 above shows, in order to arrive at a clean combustion, the engine must operate with a lean mixture and at a low temperature, both of which tend to reduce the specific engine power. Turbocharging is the means for compensating the specific power loss thus incurred.

An important method for nitric oxide (NO_x) reduction in the exhaust gases is the Exhaust Gas Recirculation (EGR), which can be realized either as a low-pressure or a high-pressure variant, or a combination thereof. The high-pressure EGR can not be implemented without turbocharging; especially in the case of large engines because of the positive pressure difference across the engine. Referring to Fig. 4 below, it is clear that the cleaned exhaust gas, whose pressure is further reduced in the particle filter and/or catalyst, must be compressed before being introduced into the air receiver of the engine.

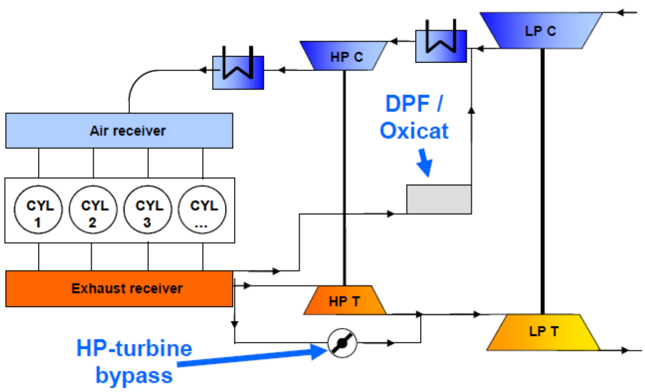

Figure 4. A high pressure EGR schema [7]

HISTORICAL REMARKS

As already mentioned, the first turbocharging patent is now almost 110 years old. The patent claim (see. Fig. 5 below) specified a turbine driven by the engine exhaust gases, and a centrifugal compressor supplying the engine with compressed air, all on the same shaft. Therefore, the invention specified both forced cylinder induction and a parallel connection of the turbine with the engine crankshaft, the latter being referred to as compound engine.

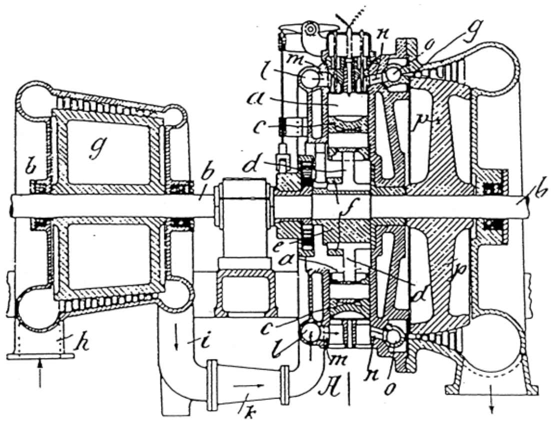

Figure 5. The Büchi compound engine and turbocharger of 1905

This patent was followed by another three, whereby the one of 1925 is customarily referred to as the key turbocharging patent. Referring to Fig. 6 below, the patent sketch shows an eight-cylinder engine with two turbochargers, whereby the turbines are connected to two suitably chosen cylinder groups. The criterion for the cylinder grouping was to minimize the interference between the individual cylinders in their respective exhaust phases, which could come about if an exhaust pulse from a cylinder would arrive at the exhaust valve of another one just at the moment of the latter's opening. In this way, the major part of the energy contained in the large-amplitude waves created by the exhaust pulses would be used for accelerating the turbine instead of being wasted in the wave reflections at the cylinder boundaries. This method is still in use today, augmented by special design features of the exhaust manifolds [8][9].

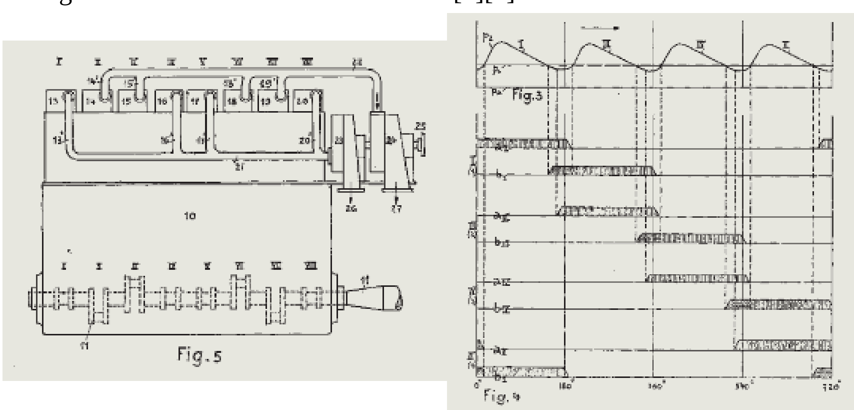

Figure 6. The Büchi pulse charging patent of 1925

The first turbocharged engine appeared in 1917. The turbocharger was designed by Prof. Rateau, and consisted of a tungsten steel turbine and a compressor with straight blades, rotating at max. 35000 rpm. It was mounted on a Renault aircraft engine, but due to a disappointing performance was later replaced by a mechanical supercharger [10].

This attempt was followed 1918 in the same application area, i.e. that of the military aircraft, by the design of S.A. Moss [10]. This one was a success, leading almost immediately to series production that extended throughout the entire World War II. Most of American WW II aircraft were equipped with turbochargers, whereas the European ones used almost exclusively mechanically driven superchargers.

The first commercially built turbocharger for a large engine was delivered in 1924 by the Swiss company Brown Boveri of Baden (BBC) to Swiss Locomotive & Machine Works (SLM) of Winterthur [3]. It was a single turbine, two-stage compressor design, delivering air at a pressure ratio of mere 1.35 to the scavenging blowers of a two-stroke Diesel engine running on a test stand.

The first two maritime vessels to become turbocharged Diesel engines as the main propulsion units were the sister ships *MS Preussen* and *MS Hansesstadt Danzig*, commissioned in 1927, and each fitted with two 10-cylinder, four-stroke Vulkan-MAN engines. The design and calculations of the turbocharging were done under the supervision of A. Büchi, and the engines employed Brown Boveri turbo-blowers.

The first two-stroke turbocharged Diesel engine had to wait until 1946 to be commissioned in the power station of Sulzer Works in Winterthur; and another six years passed before the first two-stroke, 6-cylinder unit made by Burmester & Wain, entered operation at high seas on board of a tanker *MS Dorthe Mærsk*. The engine was turbocharged by two Brown Boveri units that increased its power from 5530 to 8000 HP, which roughly corresponds to the charging pressure of 1.5 bar [2].

Although the advantages of turbocharging were apparent, the development proceeded rather slowly; it took 25 years after the first four-stroke marine Diesel engines were commissioned to see the first two-stroke Diesel engine on a ship. Generally, it was after the World War II that the development of turbocharging in the large engine sector accelerated, making it possible to replace the steam turbine as the main propulsion means at sea, and the steam engine on the rail.

The first turbocharged gasoline engines for passenger cars appeared in 1962, propelling the Oldsmobile Jetfire and Chevrolet Convair Monza models of GM Company. Due to reliability and performance issues, they did not have much success, and the sales almost stopped in 1965.

The first passenger car with a turbocharged Diesel engine was the Mercedes-Benz 300SD, released for sale only in the U.S.A. The car remained on the U.S. market until 1985, but the engine was also offered in Europe in other Daimler-Benz models, to be replaced by a more modern version in 1986.

Each of the above development areas will be dealt with in more detail in the Chapters that follow.

However, there is a subject common to all turbocharger application areas that must be briefly mentioned here. First turbochargers and their successors remained for quite a long time self-contained machines, practically custom-designed for a given engine. However, matching a set of two rotational machines connected by a common shaft to a positive-displacement machine, i.e. the engine, over a wide range of operating conditions represents an almost impossible task due to the widely differing characteristics of the turbocharger and the engine. While the matching task is somewhat simpler in the case of large engines because of the well-defined operational lines, achieving good matching over the operational areas of road vehicle engines cannot be made without some form of control over the characteristics of the turbocharger. In principle, the control function can be realized by varying the respective geometries of the turbine and the compressor and/or by manipulating the flow through the machine.

Since varying the compressor geometry is very difficult to accomplish, especially in the case of highly-optimized machines, and the turbine geometry is more amenable to being varied, many control devices have been developed for this task. Referring to Fig. 7 below, the most frequently used devices either vary the geometry of the turbine stator (commonly referred to as variable turbine geometry (VTG)), or change the cross-sectional area of the channels supplying the hot gas to the rotor.

Figure 7. Turbocharger turbine control elements [10]

The gas flow control concepts consist of placing valves of various design into the turbine and/or compressor gas conduits, varying thus the mass flow rate through the respective machines. Some of the traditional and new valve designs are shown in Fig. 8 below.

Modern turbocharging concepts involve sophisticated control schemes in order to achieve optimal engine characteristics over the entire operating area. Since the subject of turbocharger control is a rather special area, its treatment is beyond the scope of the present paper. However, it should be borne in mind that they nowadays represent an inseparable part of any turbocharged system.

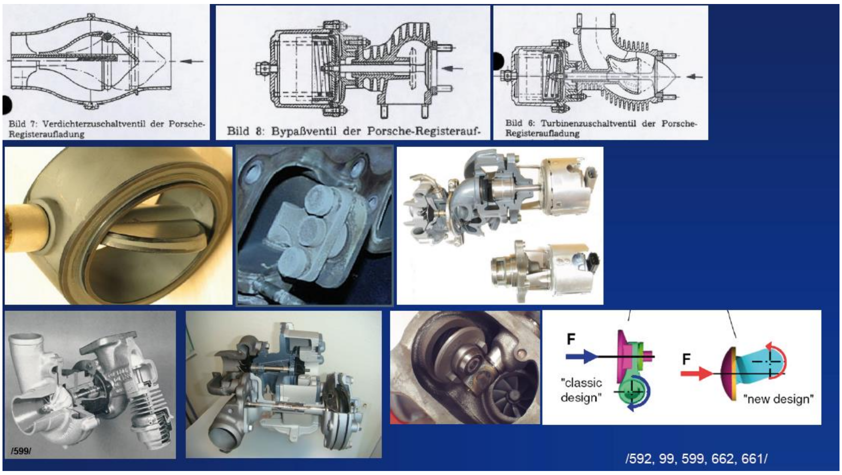

Figure 8. Gas flow control elements [10]

LARGE ENGINE TURBOCHARGING DEVELOPMENT

The large engine sector consists of Diesel and gas engines with a turbocharged power, i.e. power per turbocharger unit, of more than 500kW. The Diesel engines are furthermore divided into the two-stroke and four-stroke groups.

The two-stroke Diesel engines are almost invariably large, slow-running (n < 180 rpm) units, the chief application areas being ship main propulsion and stationary power generation plants. With thermodynamic efficiencies of the order of 55% they, together with combined-cycle gas turbines, represent the most efficient thermal machines available today. Due to their size, they are generally equipped with several turbochargers.

The four-stroke Diesel engines are used in a number of application areas, such as ship main propulsion, ship auxiliary services (e.g. electricity generation), stationary power plants, locomotives, and heavy off-road machinery. They are customarily divided into the low-speed (up to 300 rpm), medium-speed (300 – 1000 rpm), and high-speed (> 1000 rpm) groups.

Large gas engines represent an environmentally-friendly prime mover group, since the advantages of gaseous fuels in this regard are well known. However, sophisticated turbocharging and control systems are required in order for them to achieve performance figures comparable to large Diesel engines [1]. Their main application areas of large gas engines are gas transport (driving piston compressors recompressing the gas transported through pipelines), and the production of electrical energy.

In turbocharging, it is the combination of the boost pressure and mass flow rate of the turbocharger compressor that defines the engine performance. Referring to Fig. 9 below, where the development of the compressor pressure ratio of Brown Boveri (now ABB Turbo Systems) turbochargers with time is taken as an example, there has been a steady increase in the available boost pressure ever since the first units were manufactured, making it possible to achieve remarkable degrees of downsizing in the large engine sector [11].

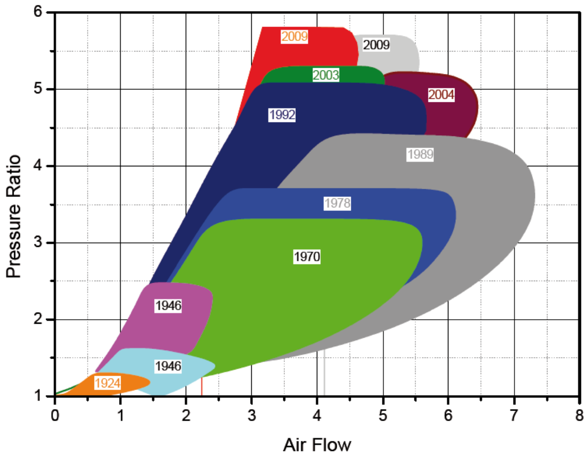

Figure 9. The development of the compressor pressure ratio of ABB turbochargers

Large engines typically operate along well-defined operation lines, such as e.g. the so-called propeller, or generator lines, which makes them amenable to a high degree of optimisation. As a consequence, the corresponding turbocharger compressor performance maps are rather narrow, extending to high charging pressures (see the LHS diagram in Fig. 10 below, showing the map of a modern ABB A140 turbocharger compressor for four-stroke engines). Road vehicles, on the other hand, must operate over a wide range of operating conditions, which in turn requires broad compressor maps. Since the delivery (boost) pressure and the mass flow rate are in opposition to each other when designing a centrifugal compressor stage, small engine turbocharging compressors generally have lower end pressures.

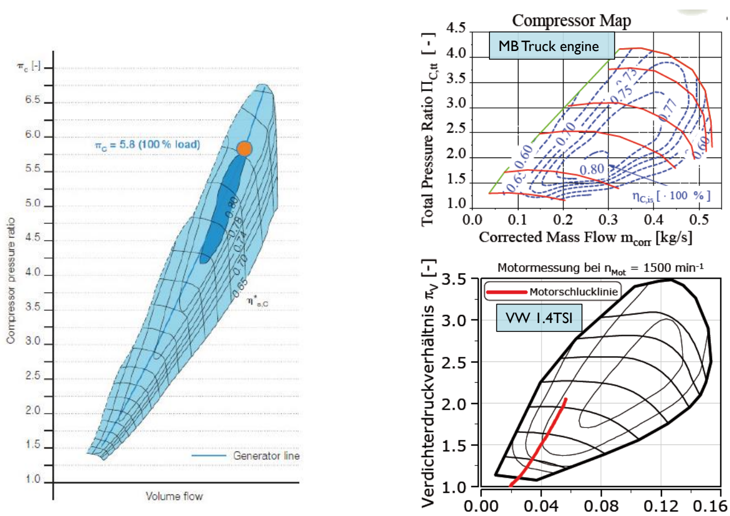

Figure 10. Compressor maps of large and small engine turbochargers

Although the high compressor pressure ratios of modern four-stroke large engine turbochargers make it possible to achieve high specific powers, meeting the current and future exhaust gas pollution norms without sacrificing the fuel economy calls for changes in the engine thermodynamics as well. One of the most capable ideas in this regard is the so-called Miller process, the application of which results in lower gas temperatures in the cylinder, reducing thus the production of nitric oxides in the combustion phase [8]. However, the Miller process needs much higher charging pressures than are possible even with the most modern single-stage compressors. Thus two-stage turbocharging has been developed, consisting of two turbochargers in series, capable of attaining charge pressure of the order of 10 bar [12]. The need for even higher boost pressures led to the development of the second generation of two-stage machines with pressure ratios increased by another 20% over the first generation ones [13].

Referring to Fig. 11 below, the diagram on the LHS shows a comparison of the ABB Turbo Systems two-stage turbocharging compressors of the first and second generations. The latter is characterized by a higher delivery pressure, but also by a broader map at higher pressure ratios.

The RHS diagram in Fig. 11 is more significant for judging the performance of the two-stage turbocharging, and especially of the 2nd generation. Plotted in the diagram is pressure difference across the engine as a function of the boost pressure ratio, with the turbocharger efficiency at two turbine inlet temperatures as parameter. It is seen that the turbocharger efficiency has been increased from 0.6 in the single-stage case to 0.75 in the 2nd generation of the two-stage one. At the same time, pressure difference across the engine has been considerably increased, which translates into fuel savings at lower NOx emissions. The interested reader is referred to the original article [13] for further details, especially as regards the trade-offs between the fuel consumption and exhaust emissions.

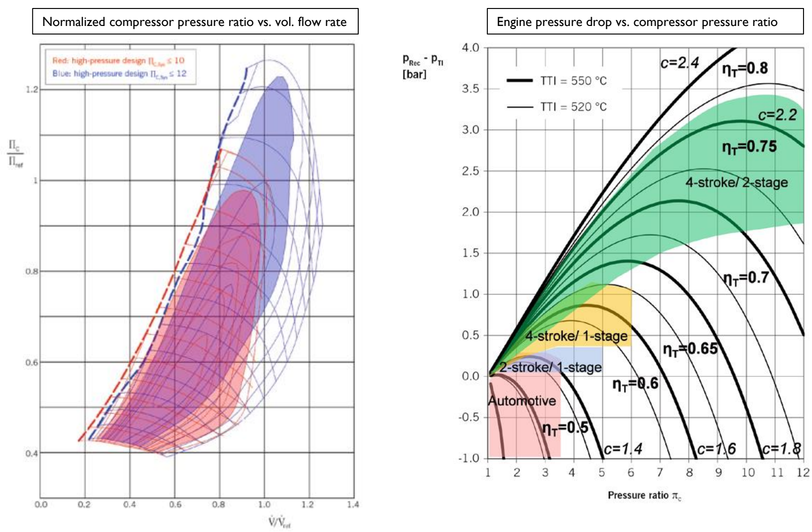

Figure 11. Performance maps of the 2nd generation of ABB two-stage turbochargers [13]

A good example of the potential already realized with two-stage turbocharging is the first large gas engine employing this technology. The engine is the 24-cylinder, 4.4 MW, GE-Jenbacher J624, driving a generator [1]. In comparison with the previous, single-stage turbocharged version with an electrical efficiency of 38%, the new one has an efficiency of 46.5%. The authors claim that by combining the engine with an excess heat recovery system, total efficiency of over 90% may be possible.

Increasing the BMEP (Brake Mean Effective Pressure) is also a means for increasing the engine power density. Newest research into the effects of raising the BMEP from 26 bar (routinely attainable with single-stage turbocharging) to 40 bar (peak cylinder pressure of 365 bar), carried out with a special single-cylinder experimental engine at the Hamburg University of Technology ([14][15]), revealed that meeting the IMO Tier II limits is possible with a simultaneous and remarkable fuel efficiency improvement. Major part of this success is due to two-stage turbocharging (gas exchange improvement) and Miller timing [15].

TURBOCHARGING OF COMMERCIAL VEHICLE DIESEL ENGINES

As already mentioned above, turbocharging of truck and bus Diesel engines commenced in 1938 in Switzerland with the production of the Saurer 8.55 litre BLD engine charged by a Brown Boveri turbocharger with a boost ratio of 1.4, increasing thus the engine power from 73 to 100 kW. As already mentioned, main reason for the introduction of turbocharging was to compensate for the power loss the naturally aspirated engines experienced when operating at high altitudes in Swiss Alps.

Referring to Fig. 12 below, the turbocharger can be seen in the upper right part of the engine. Clearly visible are the two exhaust pipes feeding the turbine, realizing thus the Büchi patent of 1925 as a two-pulse system. The latter is known to provide a faster acceleration of the turbocharger turbine by utilizing the energy of the large-amplitude waves being generated in the exhaust manifolds as a consequence of the cylinder discharge process. Fast turbine acceleration is instrumental in minimizing the so-called turbo hole, i.e. the delay in the engine power delivery in reaction to the demand signalled by the vehicle driver. Clearly, this is of special importance in the case of a heavy vehicle on a steep mountain road.

Apart from this engine and its derivatives, there were practically no further turbocharged engines of importance in the commercial road vehicle sector until the release of the MAN D1546 6-cylinder, 8.3 litre engine in 1951, and the Scania 8-cylinder, 11 litre engine in 1953, both with Brown Boveri turbochargers, operating in the pulse-charge mode. Mercedes-Benz also did some work on turbocharged truck engines at that time, but the application was limited to special vehicles, remaining so for another 30 years [16].

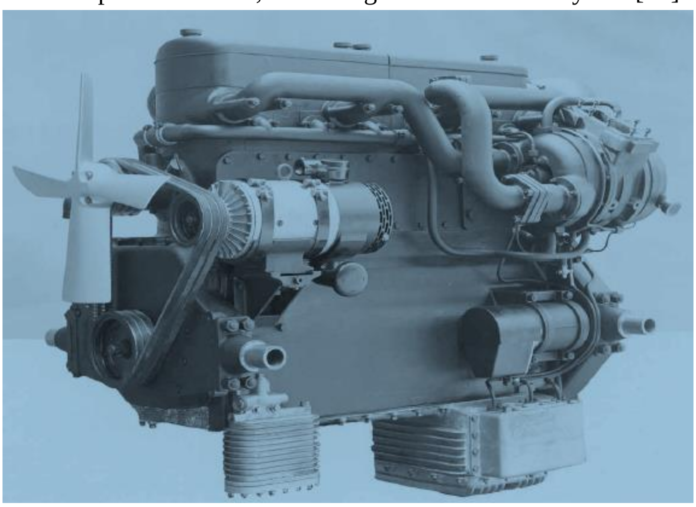

Figure 12. Saurer BLD engine with a Brown Boveri Turbocharger (1938)

Apparently, it was the exhaust gas legislation that gave rise to the intensification of the development and application of turbocharging to commercial vehicle engines, as witnessed by the Mercedes-Benz timeline in this area [16]. Referring to Fig. 13 below, there is a clear trend towards turbocharged engines from about 1980 onwards, i.e. from the time when the first exhaust gas legislation came into effect.

The accelerated development of turbocharging in this area has resulted in modern engines meeting all the relevant emission control norms. State of the art nowadays is single-stage, regulated turbocharging, although there is also a two-stage turbocharged MAN D2676 engine that meets the Euro VI and IMO Tier IV exhaust emission norms.

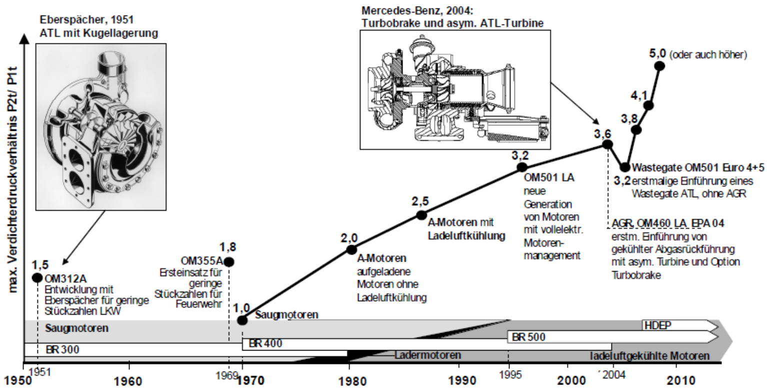

Figure 13. Mercedes-Benz commercial vehicle Diesel engine timeline [16]

However, in conjunction with the turbocharging of commercial vehicle engines there are two developments worth of being specially mentioned. The first one relates to the first patent application of Büchi in 1905 (the compound engine), whereas the second one deals with using the turbocharger as a vehicle braking device.

Compound Diesel engines have been designed and used in the past, but always in rather specialized fields, such as aircraft propulsion, e.g. Napier Nomad I and II [18], or the Zvezda M503 engine for military marine applications [17]. However, since the introduction and series-production of the Scania 11L turbo compounded engine in 1991, all major Diesel engine manufacturers have such systems in the production programs.

The Scania system (see Fig. 14 below) consists of a power turbine connected to the engine crankshaft by means of a hydraulic coupling and a gear reductor. Reportedly, such systems bring about BSFC efficiency increases of 5% on the average, but have also drawbacks in being complicated, bulky, and expensive. The new research seems to favour turbo generators as a more efficient, and easier to apply and control, solution for future designs [20][21].

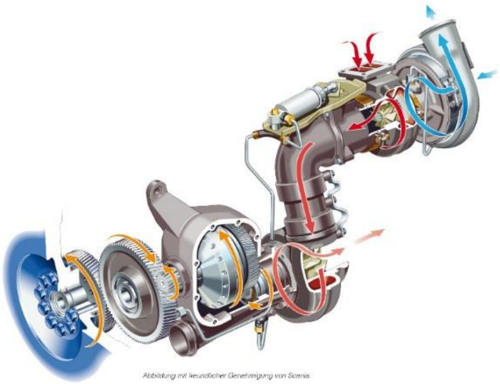

Figure 14. The Scania 11L engine turbo compounding system [19]

Turbo-braking is an interesting extension of the turbocharging in that the turbocharger is used as a brake by manipulating the gas flow cross-sectional area of the turbine. The need to develop this kind of a non-friction brake arose from the deficiencies of the standard Diesel engine retarder, such as temperature limits, fading action, weight, costs, etc. [16]. This solution disposes with the standard retarder throttle downstream of the turbine, replacing it with a redesigned, variable cross-sectional area, twin-scroll turbocharger turbine. The large mass flow rate available to the turbine at braking drives the compressor, which in turn charges the engine at high pressure, transforming the latter to a charged piston compressor. Braking power values of the order of 50 kW/litre of engine displacement have been realized with this system, which make it possible to increase the mean truck velocities in the long-haul road transport without having to invest into more powerful friction brakes [16].

PASSENGER CAR DIESEL ENGINE TURBOCHARGING

While the Mercedes-Benz 300SD of 1974 was the first series-produced turbocharged passenger vehicle, it remained the only one of this kind for almost 15 years. The turbocharged Diesel breakthrough in the passenger car market began with the introduction of the Audi 5-cylinder, 2.5 litre engine in 1989. Although preceded by the launch of the Fiat Croma 3.0 TD i.d. (*iniezione diretta*) in 1986, due to the latter being restricted for sales at the Italian market only, it was the Audi engine that created the necessary impact for the breakthrough to happen.

Passenger cars driven by naturally aspirated Diesel engines have been available long before the turbocharged ones came to the market, but the strengthened exhaust emission norms made a new concept necessary. The solution found was based on a combination of direct injection and turbocharging.

An exemplary overview of the Diesel engine development for passenger cars can be seen in the Mercedes-Benz timeline of Fig. 15 (the 300SD data added by the present author). It can be seen that the 300SD was better in terms of the specific power and torque than the 1983 2.5 litre, naturally aspirated engine of more modern design. The first common rail, direct injection, turbocharged engine was introduced in 1997 as a precursor of a very successful engine series, with the most recent one attaining the average fuel consumption of 4.1 l/100km. The engine version of 2014 and its predecessor of 2011 are equipped with a sophisticated two-stage turbocharging that includes gas path control actuators.

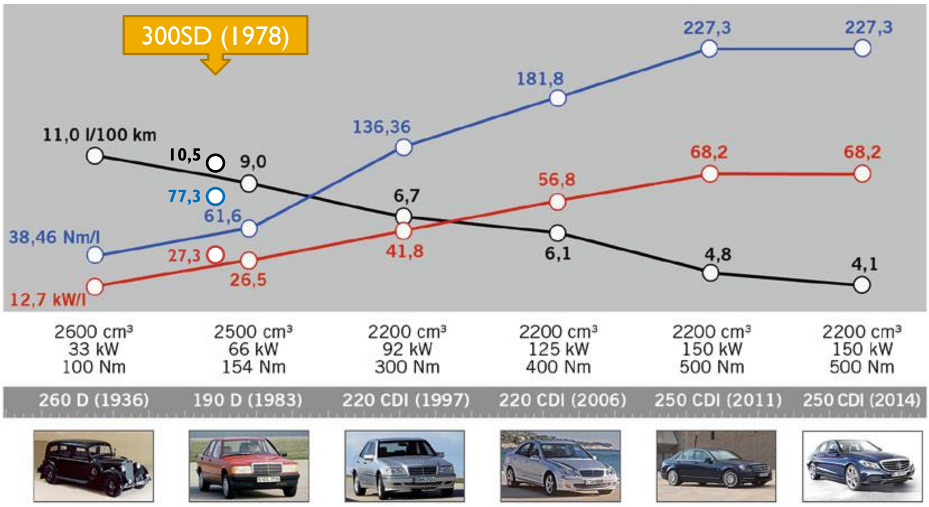

Figure 15. The Mercedes-Benz passenger car Diesel engine timeline [22]

An example of a modern two-stage turbocharged engine is presented schematically in Fig. 16 below. The engine in question is the VW/Audi 2.0 TDI, turbocharged by the Borg Warner R2S turbocharger with a single air cooler. Both turbochargers have fixed geometries, the control being effected by means of three valves in the air and exhaust manifolds. In addition, there is also a high-pressure EGR system, operating on the positive pressure difference between the exhaust and air manifolds (unlike the large engines, where the opposite is the case). With variations in the turbocharging tract, the engine is used in both passenger cars and light commercial vehicles.

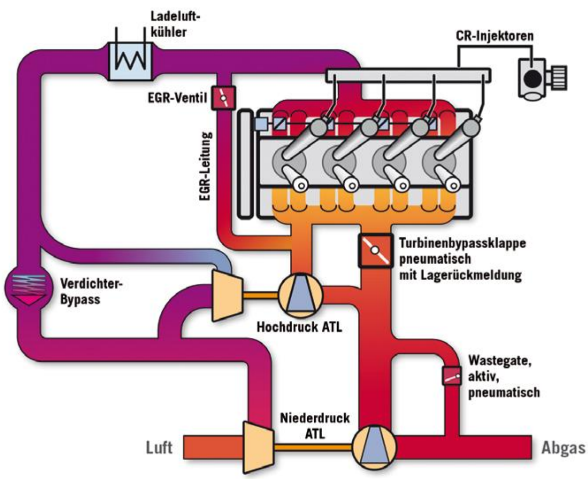

Figure 16. The VW/Audi 2.0 TDI engine [23]

The turbocharging control areas of the engine are shown in Fig. 17 below [8]. The engine map is shown in terms of torque vs. engine speed, with the shaded areas designating constant BSFC values. At low and high engine speeds, the turbocharger is running in the two-stage and single-stage configurations, respectively, whereas both machines are at various individual degrees of part-load in the middle region of the map. The map also shows that full torque is available at very low engine speeds, which is characteristic for all modern Diesel engines.

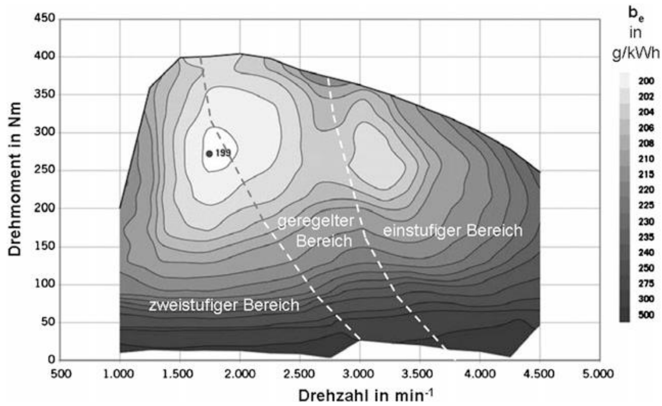

Figure 17. The control areas of the VW/Audi 2.0 TDI engine [8]

Two-stage, controlled turbocharging represents the state-of-the-art with the passenger car Diesel engines of today. According to Borg Warner [24], this concept is adequate at power densities of up to approx. 75 kW/litre. Three-stage turbocharging has already been applied, as in e.g. BMW 6-cylinder, 3.0 litre engine, bringing about a BSFC improvement of at least 8% [24].

PASSENGER CAR GASOLINE (OTTO) ENGINE TURBOCHARGING

After the limited success with the turbocharging of the two GM models in 1962, and considering the general tendency towards knock when the gasoline/air mixture is compressed to high pressures, turbocharged gasoline engines were not mass-produced until recently. Porsche seems to be the only manufacturer to have had turbocharged gasoline engines in the production program from 1974 onwards. But, as the Fig. 18 below clearly shows, the reason was not increasing the fuel efficiency, but rather improving "the pleasure of driving".

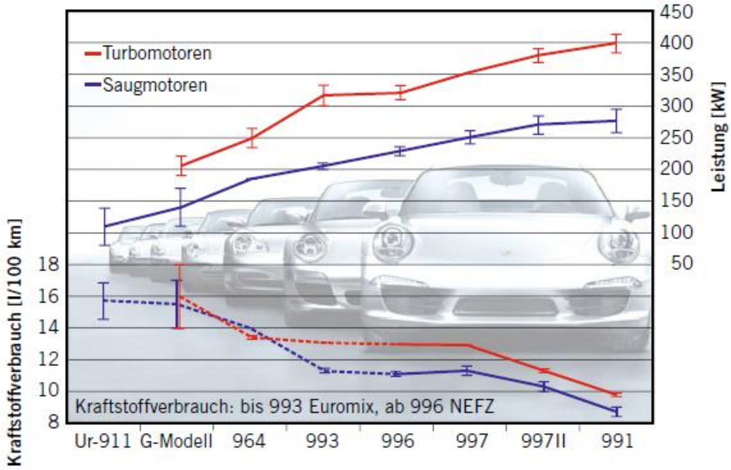

Figure 18. The Porsche 911 gasoline engines from 1974 until today [25]

Downsizing gasoline engines with fuel injection into the inlet channels was not successful, and the need thus arose for a different concept, namely direct gasoline injection into the engine cylinders. Bearing in mind that most WW II aircraft engines were equipped with this fuel supply system and were also supercharged, this concept was not entirely new. But apart from the Mercedes 300SL of 1953, which had a naturally aspirated engine with direct gasoline injection, no other engine manufacturer seems to have had such an engine until only recently, most probably on cost grounds.

However, inspecting the Mercedes-Benz gasoline engine timeline of Fig. 19 below, it is clearly visible that the 300SL engine was "downsized" to 50 kW/litre, a value that Mercedes only improved some 30 years later. The breakthrough with this engine type came with the combination of turbocharging and direct gasoline injection; and in order to meet the CO_2 legislation, downsizing of 50% was seen to be necessary. In addition, the norms regarding the emission of the pollution gases, especially of NO_x, can only be met in conjunction with other means, such as EGR, variable valve timing, etc.

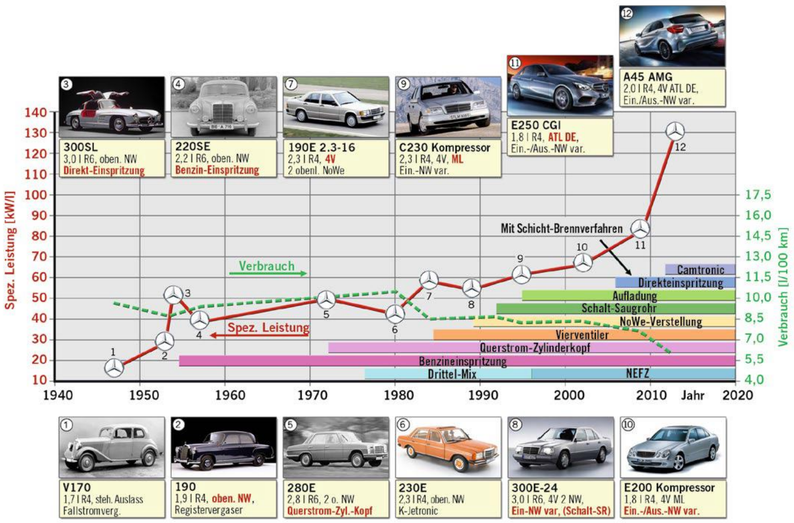

Figure 19. The Mercedes-Benz gasoline engine timeline [22]

The first downsized gasoline engines with direct fuel injection appeared some ten years ago. A characteristic example of the new engine generation is the VW 1.4 TSI, 132 kW engine, which in the first version of 2005 had a turbocharger and a Roots compressor. The torque curve was shifted towards low engine speeds, similar to the modern Diesel engines. The development of the new technology has been very fast, such that the internal efficiency of a GDI engine is now close to the values characteristic of modern Diesel engines [22].

The chart in Fig. 20 below illustrates the relationship between the engine power and specific power for various values of the displacement volume (the engine examples have been entered by the present author). The diagram also shows the limits of single stage turbocharging as of 2010 [26]; and it is also seen that two example engines from the current production are still below the downsizing limit possible with single-stage turbocharging. However, further development of single-stage turbocharging with a segmented (twin-scroll) turbine on a four-cylinder Mercedes-Benz engine clearly demonstrates further downsizing potential, reaching a specific power of 115 kW/litre simultaneously with a fuel consumption reduction by almost 20 g/kWh [33]; and one current GDI engine for sport cars (Mercedes

AMG 265 kW with a single-stage, twin-scroll turbine) demonstrates the downsizing potential of single-stage turbocharging taken to the extreme (see also engine No. 12 in Fig. 19 above).

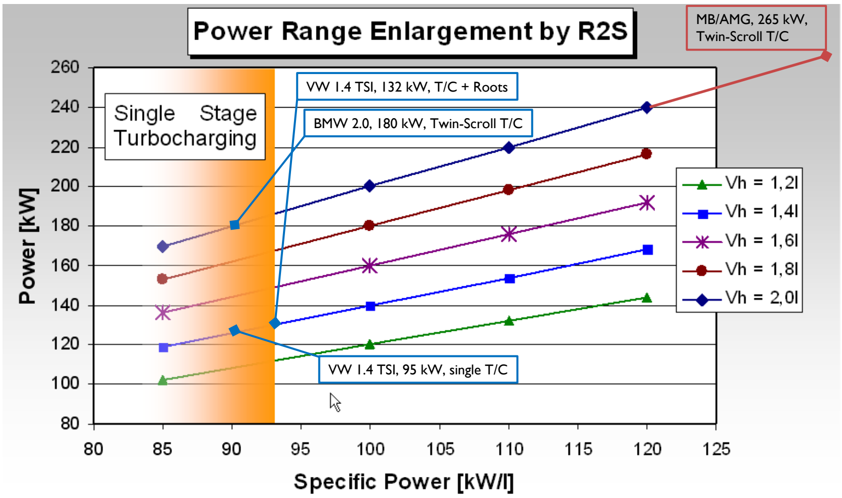

Figure 20. Downsizing possibilities and current engine examples [26]

Note that that on account of its firing order, the four-cylinder engine is the most difficult one to turbocharge; and in order to minimize the interference between the neighbouring cylinders, modern four-cylinder GDI engines are usually equipped with exhaust manifolds divided into two groups, which also provides for a full torque at very low engine speeds. An example of this is the Mercedes MB270 1.6 litre, 115 kW engine, which attains the full torque of 245 Nm already at the speed of 1250 rpm [8].

The turbocharged GDI engine of today is an established product, but there is still a need for further downsizing efforts, and other improvements. With regard to turbocharging, the three-cylinder engine seems to be an ideal basis platform for further development on account of its size and the ideal three-pulse exhaust pressure pattern [8]. Examples of this approach are the Ford EcoBoost 1.0 litre engine with the turbocharger integrated with the cylinder head [10], and the new PSA 1.2 litre engine [27].

One area where there is a clear need for improvement is the engine acceleration in response to the driver's demand for more torque. While most modern turbocharged GDI engines do have the full rated torque at low engine speeds under steady-state conditions, they are still behind their naturally aspirated counterparts in terms of the time needed to reach these values after a step demand (the so-called Time-to-Torque, or TTT). For example, a study by the French car part manufacturer Valeo [32] shows that a naturally aspirated engine has the specific TTT of the order of 100 $Nm/s/dm^3$, whereas a turbocharged one reaches 45 $Nm/s/dm^3$ (with a twin-scroll turbine). Referring to Fig. 21 below, it can be seen that the naturally aspirated engine needs one second to reach the torque of 240 Nm, whereas this time is about 2.7 seconds in the case of the turbocharged one. Note that the same engine equipped with a simpler turbocharger is capable of producing only 25 $Nm/s/dm^3$.

The solution proposed by Valeo consists of a small, electrically-driven auxiliary compressor, mounted on the turbocharger shaft, which is only taken into operation when the engine is about to accelerate. The total TTT (turbocharger + the auxiliary compressor) value thus achieved is 140 $Nm/s/dm^3$, i.e. higher than the one offered by the naturally aspirated engine. In this way, the main drawback of turbocharged GDI engines vs. the naturally aspirated ones as regards the vehicle acceleration can be eliminated, but there are a number of issues to be dealt with before this or similar solutions can enter the series production. These include the need for augmenting the electrical system of the vehicle with regard to voltage, battery capacity, improved charging in order to provide enough energy for frequent accelerations, etc. [35]. Examples of highly optimized engines with electro-assisted turbochargers can be found in the Formula-1 vehicles built in accordance with the 2014 regulations, e.g. [34].

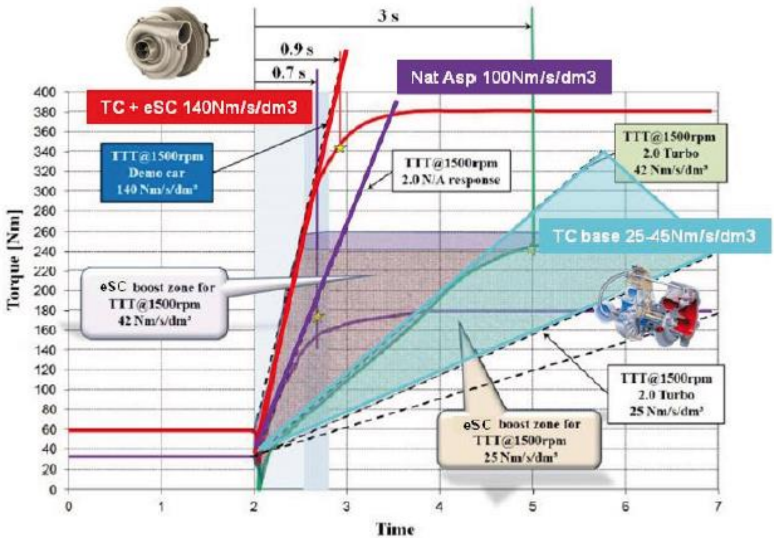

Figure 21. Torque build-up curves of various GDI engine versions [32]

Although the turbocharged GDI engine has already reached a high performance level through downsizing, there is still a considerable potential for further development. According to A. Schamel of Ford [28] and Prof. Geringer of TU Wien [36], there are possibilities for further CO_2 reduction in the two-figure percent range through downsizing; and there is an intensive activity aimed at the development and/or optimization of turbocharging concepts that should make this possible. Among the possibilities are the two-stage turbocharging in the series and parallel (sequential) connections, [29] and [30], respectively, and/or electrically-assisted turbochargers, such as e.g. the solutions of BorgWarner [31], Pankl [37], and already mentioned Valeo [32]. However, a fully-electrical turbocharging system does not seem to represent an attractive possibility at the moment [38].

The perennial subject of air management is certainly going to be actively pursued in the future; and from the standpoint of turbocharging, it primarily relates to improving the efficiency of the system components, i.e. turbine, compressor, and air path components [39].

CONCLUSIONS

- Turbocharging is one of the most important technologies for reducing the fuel consumption and exhaust emissions
- Large four-stroke Diesel and gas engines: two-stage turbocharging is a proven technology for the current and future engines

- Large two-stroke engines: advantages of two-stage turbocharging demonstrated at test stands, but the slow-steaming trend in the ship cargo transport deters investments in new technologies
- Commercial vehicle Diesel engines:
  - Two-stage turbocharging has been developed, but is not yet widely used
  - It is seen as a means for attaining the Euro VI and Tier 4 emission norms, as is e.g. the case with the MAN 2676 engine
  - Turbo-compounding and turbo-braking are established technologies
  - Passenger car Diesel engines:
  - Two-stage, regulated turbocharging represents the state-of-the-art today
  - Three-stage turbocharging has also been applied
  - In order to further improve the low-end torque, optimized compressors and turbines with variable geometry will be necessary
- Passenger car Otto engines:
  - Single-stage, regulated turbocharging represents the state-of-the-art today
  - Two-stage turbocharging has demonstrated potential for compensating the trend towards torque diminishing at higher downsizing values
  - However, some manufacturers (e.g. Daimler-Benz) see highly optimized exhaust channels, twin-scroll turbines, and/or electrically assisted turbocharges as a solution
- And a final quote: "We are still far away from the end of engineering possibilities [40].

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