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DEPARTMENT OF AUTOMOTIVE, COMBUSTION ENGINE AND RAILWAY ENGINEERING

Ústav automobilů, spalovacích motorů a kolejových vozidel

Optimization of supercharged engine with e-assisted supercharger (eBooster)

Optimalizace přelňovaného motoru s e-asistovaným kompresorem (eBooster)

MASTER THESIS

2020/21

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MASTER'S THESIS ASSIGNMENT

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

I. Personal and study details

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II. Master's thesis details

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Optimalizace přelňovaného motoru s e-asistovaným kompresorem (eBooster)

Guidelines:

1. Focus the literature research on e-assisted ICE charging systems topologies.
2. Simulate a turbocharged ICE with e-assisted compressor (eBooster) in steady-state regimes.
3. Optimise the e-assisted compressor size in the intake manifold and its function.
4. Optimise the ICE operation to maximise the overall efficiencies, respecting the real limits (maximum pressures, temperatures etc.).
5. Simulate the ICE with e-assisted compressor in transient operation with a goal of evaluation of the electrical energy demands.

(Thesis will be submitted in English language)

Bibliography / sources:

Name and workplace of master's thesis supervisor:

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Name and workplace of second master's thesis supervisor or consultant:

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Supervisor's signature	Head of department's signature	Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

17.05.2021

Date of assignment receipt Student's signature

Study program: Combustion engines
Thesis supervisor: Ing. Rastislav Toman

STATEMENT OF ORIGINALITY:

This is to certify that to the best of my knowledge, the content of this thesis is my own work. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Prague 14.07.2021

Signature

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Finally, I dedicate this thesis to my deceased grandfather, who was engineer in automotive field and despite of his respectable age he still managed to be in touch with modern technologies and even did provide me some mentoring related to this thesis.

Annotation: In this thesis potential of electrically assisted supercharging is evaluated. Thesis consists of two major parts – theoretical research of existing solutions and practical part with GT-Suite 1D simulations of supercharged engine model.

Keywords: eBooster, Turbocharger, Supercharger, Downsizing

CONTENT

NOMENCLATURE

Abbreviations

ICE	Internal Combustion Engine
NA	Naturally Aspirated
DI	Direct Injection
EGR	Exhaust Gas Recirculation
NEDC	New European Driving Cycle
A/F	Air to Fuel Ratio
RPM	Revolutions Per Minute
VGT	Variable Geometry Turbine
WG	Waste-gate
BSFC	Brake Specific Fuel Consumption
BMEP	Brake Mean Effective Pressure
A/R	Area/Radius
TC	Turbo Charger
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
RDE	Real Driving Emissions
VVT	Variable Valve Timing
ETC	Electric Turbo Compound
MGU-H	Motor Generator Unit - Heat
MGU-K	Motor Generator Unit – Kinetic
CFD	Computed Fluid Dynamics
1-D	One-dimensional
3-D	Three-dimensional
OBD2	On-board Diagnostics
PID	Proportional integrative derivative
MAF	Mass Flow sensor
MAP	Manifold Absolute Pressure
DOE	Design of Experiment
TDC	Top Dead Center
FWD	Front-Wheel Drive

Symbols

h	Enthalpy
H_u	Heat of combustion
λ	Air–fuel equivalence ratio
s	Entropy
C	velocity
p	Pressure
$\dot{m}$	Mass flow
c_p	Isobaric specific heat capacity
T	Temperature in Kelvin
η	efficiency
κ	Heat capacity ratio
n	Engine speed
r	Specific gas constant
L_t	stoichiometric ratio

1. INTRODUCTION

Increasing efficiency and power of the ICE has been the subject of investigation since very beginning of automotive industry. That might be split in two major groups: mechanical loses minimization and thermodynamic processes improvement. The main idea behind engine efficiency is transformation of a chemical energy, stored in fuel, to a kinetic energy by burning air-fuel mixture. As a result, crank mechanism rotates crank shaft and torque is produced. Therefore, the more fuel we burn, while keeping stoichiometry coefficient, the more power we get. To increase amount of fuel we also have to increase amount of oxygen (air) to keep admissible stoichiometry. Considering displacement limitations, the best way to provide more air is to increase its density and that's usually done by the use of forced induction.

Nowadays emissions and as a consequence down-sizing is an often-discussed topic. So called global warming forced governments to impose strict regulations on emissions of 'green house gases' in order to fulfill demands of eco-activists, which are convinced that cars are main source of emissions, and that led to need of rapid decrease of carbon-dioxide which consequently led to low displacement engines – so called 'down-sizing'. Yet Power requirements are on the same level which forces manufactures to offer meant-to-be highly efficient, low displacement, turbocharged or supercharged engines. Those have their advantages nevertheless there are disadvantages too which will be described detailly later.

In a nutshell, speaking of turbocharging, we are suffering with Low-end-torque vs peak power dilemma, nevertheless turbochargers are using waste energy of exhaust gases to spin and give boost which improves efficiency. On the other side superchargers are free from lag as they are connected directly to the crank and so they provide boost from almost idles but it's origin of their main con – they take energy from engine which leads to lower mechanical efficiency compared to turbocharged engines with same other conditions. To overcome those cons the new idea appeared in late 1990's – electrically assisted charging systems and that's the main subject of that thesis.

2. Downsizing

Concept of engine downsizing is defined as the use of a low displacement engine that still provides the power of a larger engine. As is shown in (1) it's possible by increasing intake pressure and as a consequence the density of air with some kind of charging system. The speed/load point is shifted to a more efficient region through reduction of engine capacity whilst maintaining the full load performance via forced induction. As was said earlier in last a few decades growing concern in general and in automotive field specifically is the production of greenhouse gases through exhaust flow, primarily CO_2. The emission limits are becoming stricter with every year and that leads automotive companies to maximize efficiency of their engines to fulfill, at least in test cycles, those limitations. Speaking of European market target group for downsized engines were mainly C, D and E segment cars. Nowadays those cars are usually equipped with 1 to 2 liters, inline 3 to 4 cylinders engines with a single or multiple stage charging system, whereas till the late 90th were mostly used naturally aspirated engines, inline 4 to V6 with displacement from 1.6 to 3 liters providing comparable power output.

$$(1) \qquad P_e = \eta_e \eta_v * \frac{H_u}{1+\lambda L_t} * V_c * \frac{\varepsilon}{\varepsilon - 1} * \frac{p_{in}}{r_{in} T_{in}} * \frac{n_m}{30 * t_s}$$

Turbocharging isn't the only one technology that facilitates higher efficiency. Direct fuel injection, advanced exhaust gas recirculation systems, variable valve timing, variable cylinder displacement and hybridization are also playing a huge role in downsizing.

With this approach modern engines provide several benefits comparing to the old ones:

- Reduction of CO_2 and NO_x emissions due to the higher efficiency and therefore lower consumption
- Decrease in the weight of engine. Reducing number of cylinders and using aluminum alloys instead of cast iron makes sensible weight reduction resulting in lower consumption, lower emissions and better handling.
- Lesser friction areas and therefore lower friction loses due to the lower displacement.

- Lower overall ICE inertia leads to better vehicle fuel economy. [1] [2] [3]

High specific power output of downsized engines however increases technical challenges and demands on engine and its parts. High boost pressure and therefore high compression ratio require robust combustion system and base engine robustness and durability. A good low speed torque and transient performance is required to keep good drivability.

Looking at all the benefits of downsized engine one may say that it's a great future of engines but everything has its price and that bring some disadvantages. Although those engines show great efficiency and fuel economy in test cycles, in real life the situation is quite different and the efficiency is lower.

Main problem with increasing power in ICE is so called knock. Charging even amplifies that problem. When using forced induction, the in-cylinder pressure and temperature gets much higher than in NA engine and that may lead to self-ignition of air-fuel mixture which may cause a severe damage to engine. There are 3 main solutions to avoid knock:

Direct injection

Fuel fog evaporates in combustion chamber and lowers temperature. DI is commonly used in last decade in almost all engines, but it has a lot of disadvantages. DI requires a high-pressure injection and uses injection system similar to common-rail system used in diesel engines and has a lot of common problems, mostly with long-term reliability. Injectors, due to the pressure of about 100 bar, are extremely sensitive to fuel quality and purity, as small particles may cause damage to nozzle on that speed.

Another problem with DI is carbonization of engine head. As EGR is used, carbon particles in exhaust gases are settling on intake ports and valves, which lowers effective cross-section area of ports, prevents valves from proper closure and causes loss of compression and burning of engine oil. Whereas in classical port injection fresh fuel mixture flushes and cleans ports.

Lowering compression ratio

Boosted engines usually have compression ratio under 9:1, that helps a lot, but it lowers the overall efficiency of the engine

Using rich air-fuel mixture

The most effective way to lower temperature and prevent knock is to enrich air-fuel mixture which obviously leads to high consumption and eliminates all the efficiency benefits.

Let's have a more detailed look at the last point. To understand the whole problem, we have to look back at origins of the whole downsizing. The main idea behind downsizing is that automobile have to produce less than allowed maximum of emissions. That's measured in standardized test cycle and in Europe before 1st September 2019 it was NEDC [4] in which cars were tested in relatively low load mode as can be seen in figure 1. That was beneficial for automotive companies, since engines were operated with low demand on power and in that scenario, with low amount of air-fuel mixture, temperature in combustion chamber was low enough to avoid knock and produce desirable fuel economy and emissions, however when there is a need for full power control unit starts to enrich

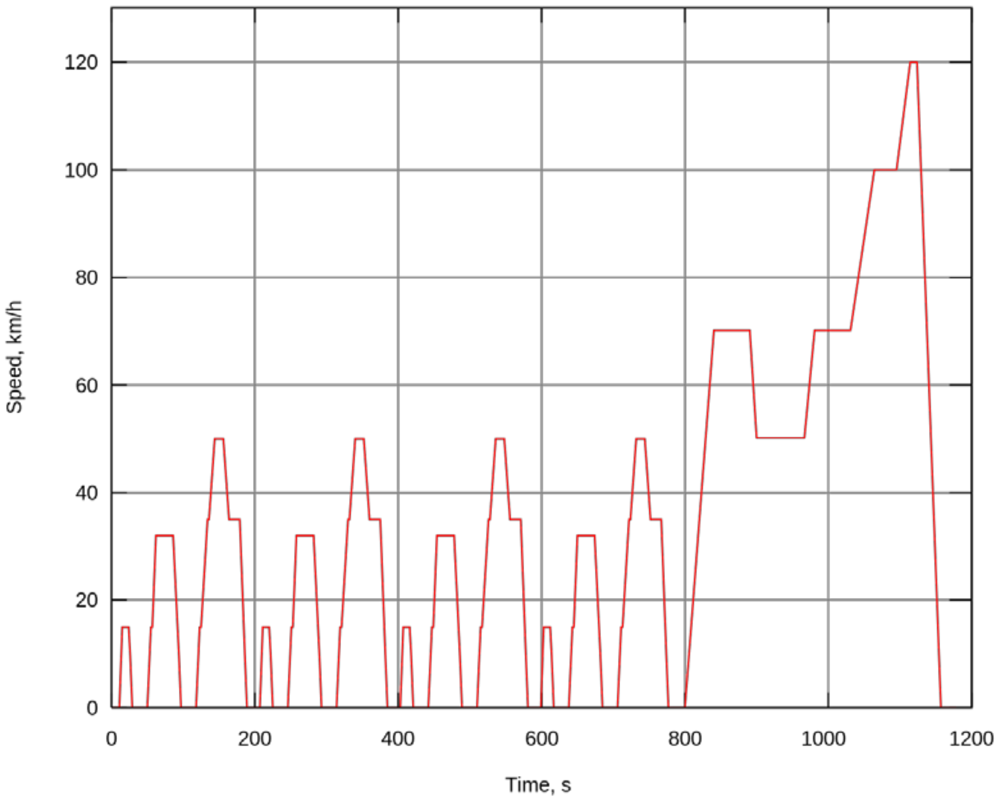


Figure 1: NEDC test cycle [28]

air-fuel mixture so the temperature can sustain low enough to avoid knock but the efficiency rapidly decreases.

Summarizing those facts, we can see that downsized engines are good for low load running, in that scenario they may actually provide great fuel economy compared to bigger engines, nevertheless in high load regimes efficiency goes rapidly down and fuel economy is worse than in case of non-downsized engines. However, with good design of the engine, control system and adequate boosting the overall efficiency is higher than in case of NA engine. [5]

3. Conventional forced induction

The power and efficiency of an internal combustion engine can be increased with the use of an air compression device such as a supercharger or turbocharger. As shown in (1) increasing the pressure and as consequence density of the inlet air will allow additional fuel to be injected into the cylinder, keeping adequate A/F ratio and increasing the power produced by the engine.

Spark ignition engines are knock limited, restricting the allowable compressor pressure increase. An intercooler heat exchanger is used with turbochargers and superchargers to cool the intake air and increase its density after the compression process has raised its temperature, and reduce the tendency to knock. Superchargers and turbochargers are used extensively on a wide range of diesel engines for decades, since it’s easier to deal with knock in diesel engines.

Since mid 2000s these tendencies became usual in petrol engines too and due to the emission limitations in last decade it even became almost impossible to fulfill these limits with naturally aspirated engines which led to almost full extinction of these.

3.1. Superchargers

Superchargers are classified as compressors that are mechanically driven of the engine crankshaft, usually via a belt drive. Superchargers are used in applications in which the increased density and pressure is desirable at all engine speeds. Philander and Francis Roots, American engineers and brothers, invented the supercharger in 1859, for use in the then-emerging steel industry. Superchargers have also been used in piston-driven airplane engines since about 1910 to compensate the decrease in air pressure and density with altitude, and to increase the flight ceiling. Since it is mechanically driven, the rotational speed of a supercharger is limited to rotational speeds around 10,000 rpm.

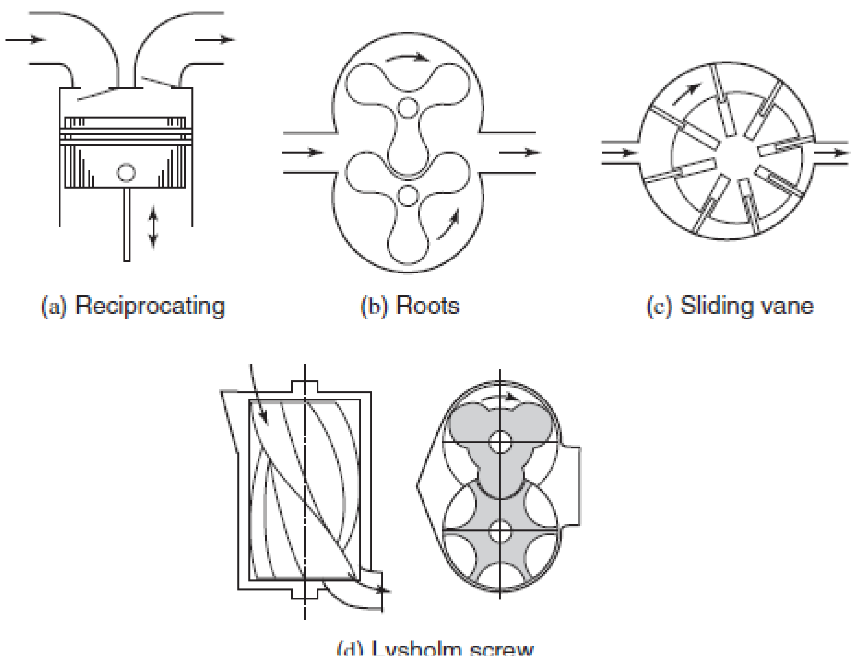


Figure 2: Types of positive displacement compressors. [7]

The types of compressors used on internal combustion engines are primarily of two types: positive displacement and dynamic.

With a positive displacement compressor, a volume of gas is trapped, and compressed by movement of a compressor boundary element. Three types of positive displacement compressors are the Roots, vane, and screw compressor, as shown in Figure 2. The efficiency of positive displacement compressors varies from about 50% for the Roots compressor to over 90% for the screw compressor.

A dynamic compressor has a rotating element that adds tangential velocity to the flow which is converted to pressure in a diffuser. Two types of dynamic compressors and turbines are radial (centrifugal) and axial.

Commonly used types of superchargers in automotive are roots, twin-screw and centrifugal.

3.1.1. Roots supercharger

Roots supercharger is the oldest design. In 1885 Gottlieb Daimler made a patent of supercharger with his own design which shared principle with the Roots brother's compressor. As figure 3 shows, there are two meshing lobes inside supercharger body that spin, trap air in pockets between them and carry it from fill side to discharge side. Air is not compressed inside the supercharger, it just blows fixed volume of air with each revolution to the intake manifold and "stack it up" which creates high pressure.

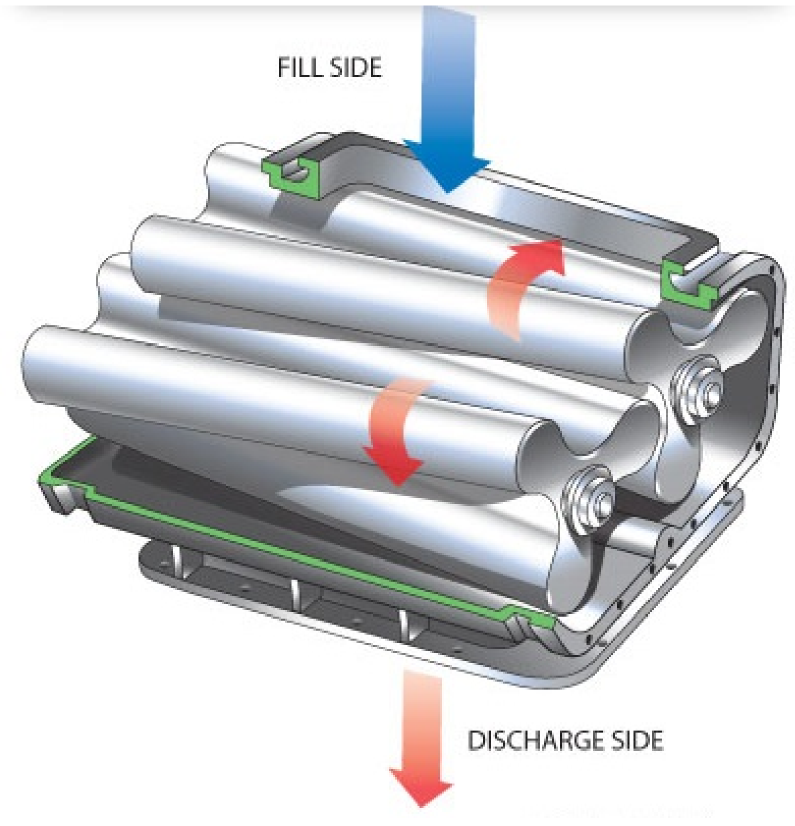


Figure 3: Roots supercharger [25]

This design has some cons:

- Fact that compression happens in the intake manifold has an unpleasant consequence, it produces a lot of heat.
- Same as all superchargers, it uses energy directly from engine and that ends in parasitic drag, although power gain from supercharger is bigger than loses, it leads to higher fuel consumption.
- Due to its construction Roots supercharger is usually heavy and have to be installed at the top of the engine which means that center of gravity is also placed higher.

Nevertheless, it has some pros:

- Power boost is instant from low RPM and is 'predictable', power gain is linear with throttle response.
- Design is simple, reliable, and inexpensive.
- No need for lubrication.

3.1.2. Twin-screw supercharger

A twin-screw supercharger is a modification of roots compressor. Figure 4 shows its principle. It operates by pulling air through a pair of meshing lobes that resemble a set of worm gears. Like the Roots supercharger, the air inside a twin-screw supercharger is trapped in pockets created by the rotor lobes. But a twin-screw supercharger compresses the air inside the rotor housing. That's because the rotors have a conical taper, which means the air pockets decrease in size as air moves from the fill side to the discharge side.

Pros:

- Thermally almost as efficient as centrifugal compressor
- Very good boost at low RPM due to very tight tolerances between rotors
- Very good reliability – virtually no wearing parts

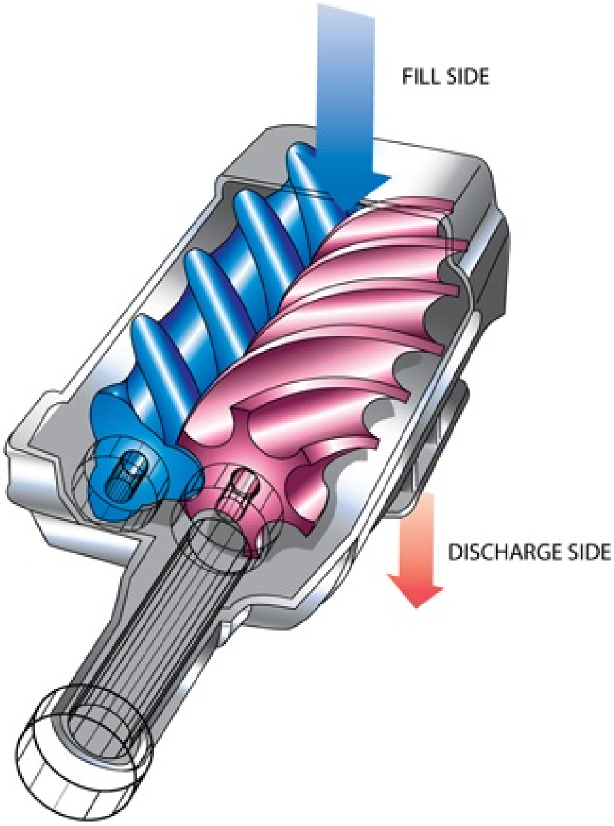


Figure 4: Twin-screw supercharger [26]

Cons:

- Price – design requires precise and therefore expensive machining
- If bypass of some sort isn't used there are loses due to internal compression ratio even when it is not sending boost to the engine (i.e. under cruising or deceleration)

3.1.3. Centrifugal supercharger

As is shown in the figure 5, the centrifugal compressor consists of a stationary inlet casing, a rotating bladed impeller, and a stationary diffuser.

Impeller is powered through gear mechanism and belt drive from a crank shaft at very high speeds to quickly draw air into a small compressor housing. Impeller speeds can reach order of 100.000 RPM. As the air is drawn in at the hub of the impeller, centrifugal force causes it to move outward. The air leaves the impeller at high speed, but low pressure. A diffuser (a set of stationary vanes that surround the impeller) converts the high-speed, low-pressure air to low-speed, high-pressure air. Air molecules slow down when they hit the vanes, which reduces the velocity of the airflow and increases pressure.

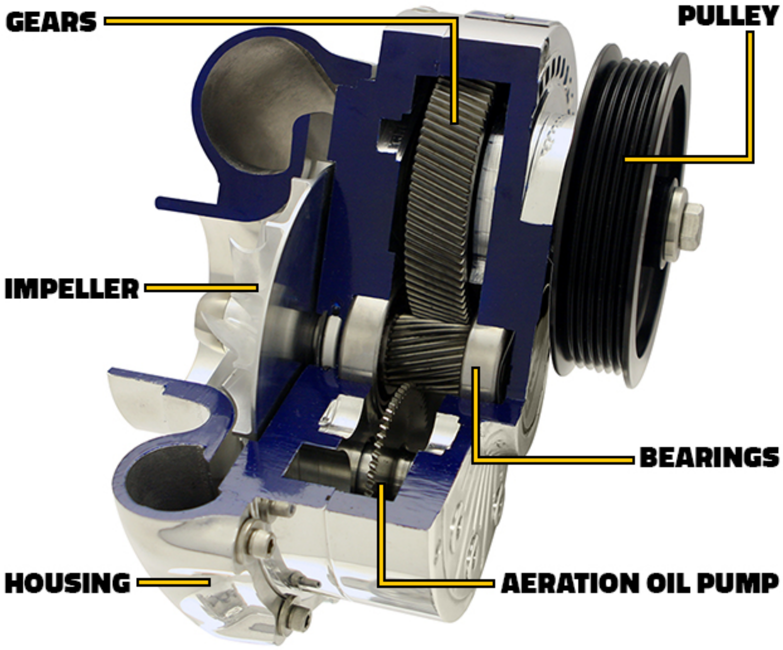


Figure 5: Centrifugal supercharger cutaway [29]

Figure 6 shows, on an h-s diagram, how each part of compressor contributes to the overall pressure. Air at stagnation state 0 is accelerated in the inlet to pressure p_1 and velocity C_1. The enthalpy change is $\frac{C_1^2}{2}$. Compression in the impeller flow passages increases the pressure to p_2 and velocity C_2, corresponding to a stagnation state 02 if all the kinetic energy were recovered. The isentropic equivalent compression process has an exit static state 2s. The diffuser, states 2 to 3, converts kinetic energy at the impeller's exit to a pressure rise (p_3-p_2) by slowing down the gas in carefully shaped expanding passages. The final state, in the collector, has static pressure p_3, low kinetic energy $\frac{C_3^2}{2}$, and a stagnation pressure p_{03} which is less than p_{02} since the diffusion process is incomplete and irreversible.

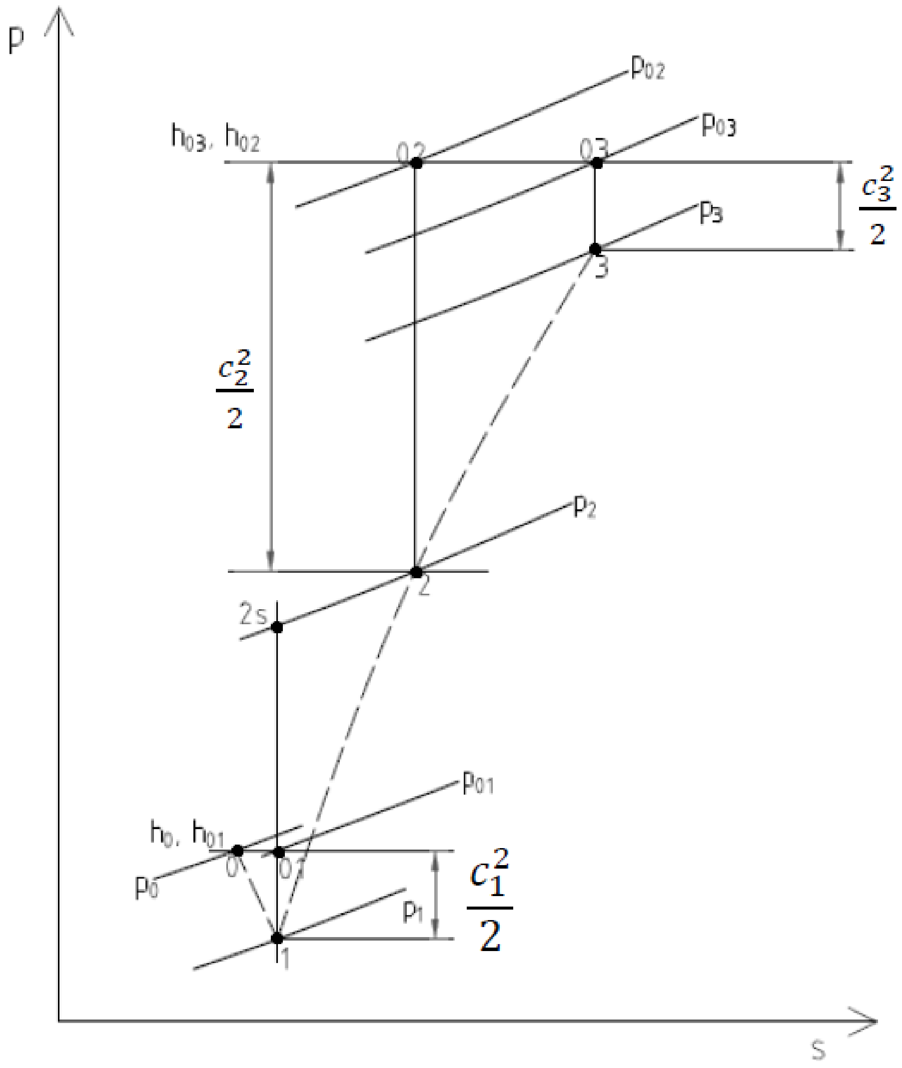


Figure 6 : Enthalpy-enthropy diagram for flow through centrifugal compressor [6]

Pros:

- Thermal efficiency – centrifugal compressors are most efficient
- Temperature – due to its design temperature isn't increasing that much
- Package – relatively small dimensions allows different options of placement
- Peak power – centrifugal compressors offer highest boost in high RPM (see figure 9)

Cons:

- Low-end torque – as it's not a fixed displacement compressor boost is growing non-linearly
- Lubrication – this design requires additional lubrication with engine oil which puts an extra demand on it.

3.2. Turbochargers

Turbochargers are defined as devices that couple a compressor with a turbine driven by the exhaust gases, so that the pressure increase is proportional to the engine speed. The turbocharger was first invented in 1906, and the applications have expanded from marine diesel engines, to vehicle diesel engines, and then to spark ignition engines.

A turbocharger is a coupled dynamic centrifugal compressor and dynamic turbine, due to the high rotational speeds, of the order of 100,000 rpm, required for efficient operation at typical ICE flow rates and pressure ratios. For automotive applications an outward radial flow geometry is used for the compressor, and an inward radial flow is used for the turbine. A cross section of a turbocharger with a radial compressor and turbine is shown in Figures 7 and 8.

A waste-gate or Variable Geometry Turbine (VGT) is used to control the exhaust gas flow rate to the turbine. The waste gate is a butterfly or poppet valve controlled straight by the intake manifold pressure or control unit through vacuum actuators to prevent the turbocharger from compressing the intake air above a set knock limit or engine stress pressure limit. More common nowadays are VGT systems which allows wider spectrum of TC usability with higher efficiency, thou these systems are more complex and expensive.

A turbine can also be mechanically connected to the engine drive shaft, a configuration called compounding. Turbochargers used in diesel locomotives use a clutch geared to the drive shaft to drive the compressor during low engine speed when there is insufficient power from the turbine. At higher engine speeds, the clutch disengages, and the compressor is driven by the exhaust gases flowing through the turbine. Axial flow compressors and turbines are typically used in marine turbocharger applications. [7]

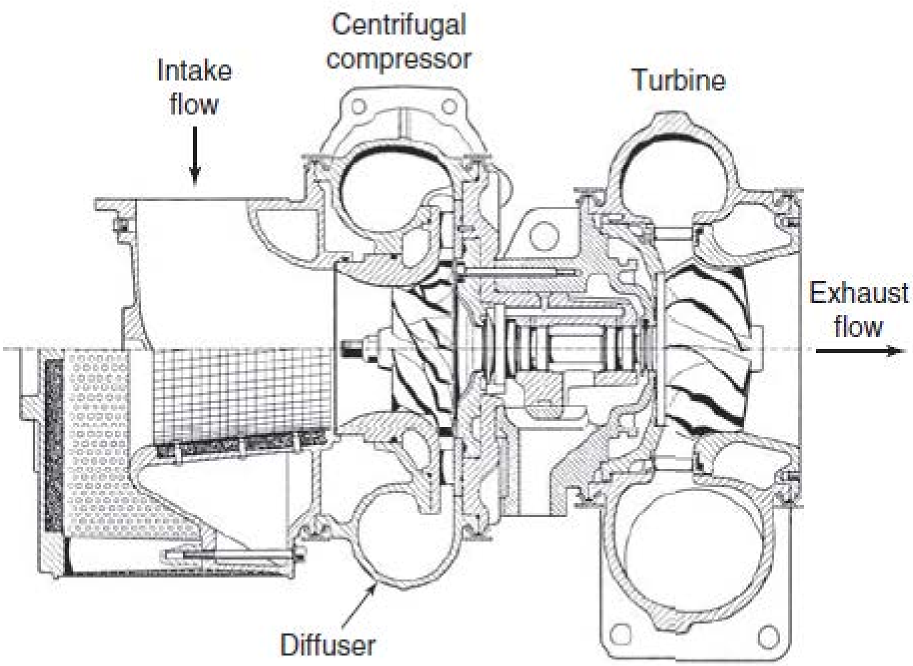


Figure 7: Turbocharger cross section (Laustela et al., 1995) [7]

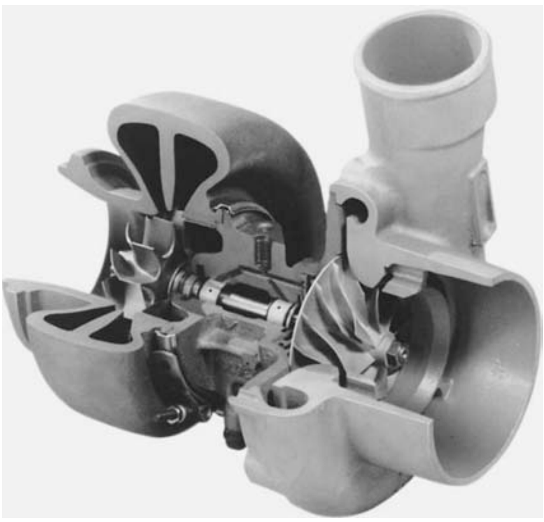


Figure 8: Turbocharger cutaway (courtesy PriceWeber) [7]

3.2.1. Turbocharger matching

This process targets at selecting turbocharger with right characteristics to achieve required torque-speed characteristics with the lowest engine BSFC. That process has various constraints. The most important is a surge margin. That can be understood by looking at figure 9. Dashed line on the left side of map represents surge line, which is the minimum mass flow rate limit below which the compressor surges. That state may cause severe damage to compressor and so turbocharger should be matched so that surge must never occur at any engine load and speed. The second constraint is that compressor must work in area under the continuous thick line on the top to right side of map above which choke will occur, since in that case compressor would not be able to deliver desired mass flow rate. Third constraint is that maximum designed turbocharged rotational speed must

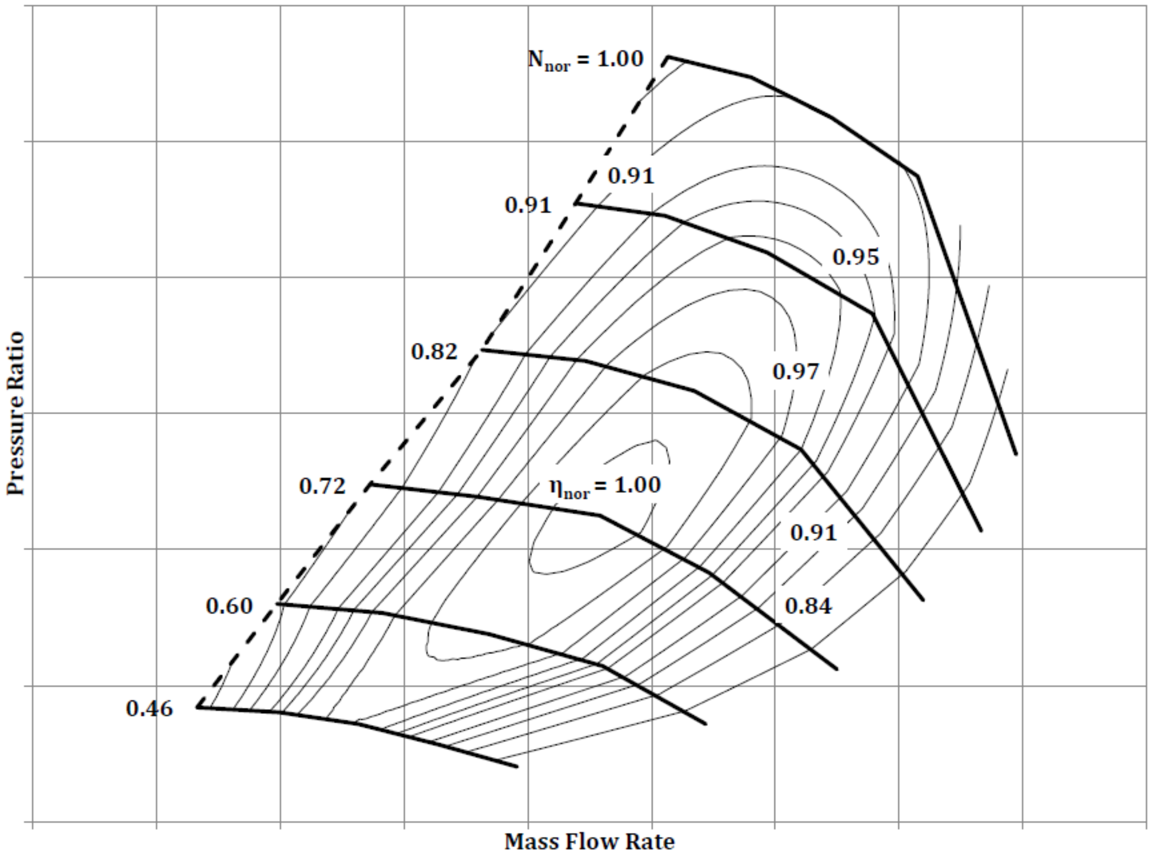


Figure 9: Typical turbocharger compressor performance map. N_{nor} stands for normalized rotor speed and η_{nor} stands for normalized isentropic efficiency. The dashed line on the left side of the map represents the surge line. [8]

not be exceeded. That constraint is usually fulfilled due to waste-gate system, that works as a bypass and is activated by the compressor outlet pressure. Because the compressor outlet pressure is a function of rotational speed, when the pressure which corresponds to the maximum turbocharger speed is exceeded, the turbine bypass is opened. This reduces the turbine power and prevents the turbocharger from further accelerating. If the turbine is of the variable geometry type, the waste-gate is not present, and over-speeds are avoided by opening the turbine vanes.

The main target of the matching process is that the turbocharger must be able to deliver the boost necessary to achieve the required engine power output and soot emissions. In a turbocharger which has a nozzle-less fixed geometry turbine, this is mainly achieved by tuning the turbine volute inlet area/radius (A/R) ratio. A turbine with a low A/R ratio restricts the exhaust flow more than a turbine with a high A/R ratio, resulting in a higher turbine expansion ratio and power. This means that by tuning the turbine A/R ratio the engine boost is adjusted. In a turbocharger which has a variable geometry turbine (VGT) the nozzles angle can be varied dynamically to adjust the turbine swallowing capacity. This is equivalent to changing the A/R ratio in a nozzle-less fixed geometry turbine.

Within the constraints of compressor operation and minimum engine output torque outlined above, the compressor is selected so that it operates in the high efficiency region of its performance map, and the turbine inlet A/R ratio is selected to achieve the boost at which the best engine efficiency occurs. Optimum boost depends on the turbine and compressor efficiency, on the combustion process within the cylinders and on the energy available in the exhaust gases. As a consequence, this optimum boost changes depending on the engine loading and speed conditions, and the turbocharger must be matched considering the typical work cycle of the engine. The drawback of optimizing the engine boost for efficiency is that, for most applications, the resulting engine transient response is unsatisfactory. To overcome this issue, the boost pressure is typically set to be higher than the best efficiency boost, with the result that the brake specific fuel consumption increases. [8]

3.3. Summarizing facts and comparison

Basically, the advantages and disadvantages of each type of boosting depends on standpoint, whether it's efficiency standpoint or drivability standpoint.

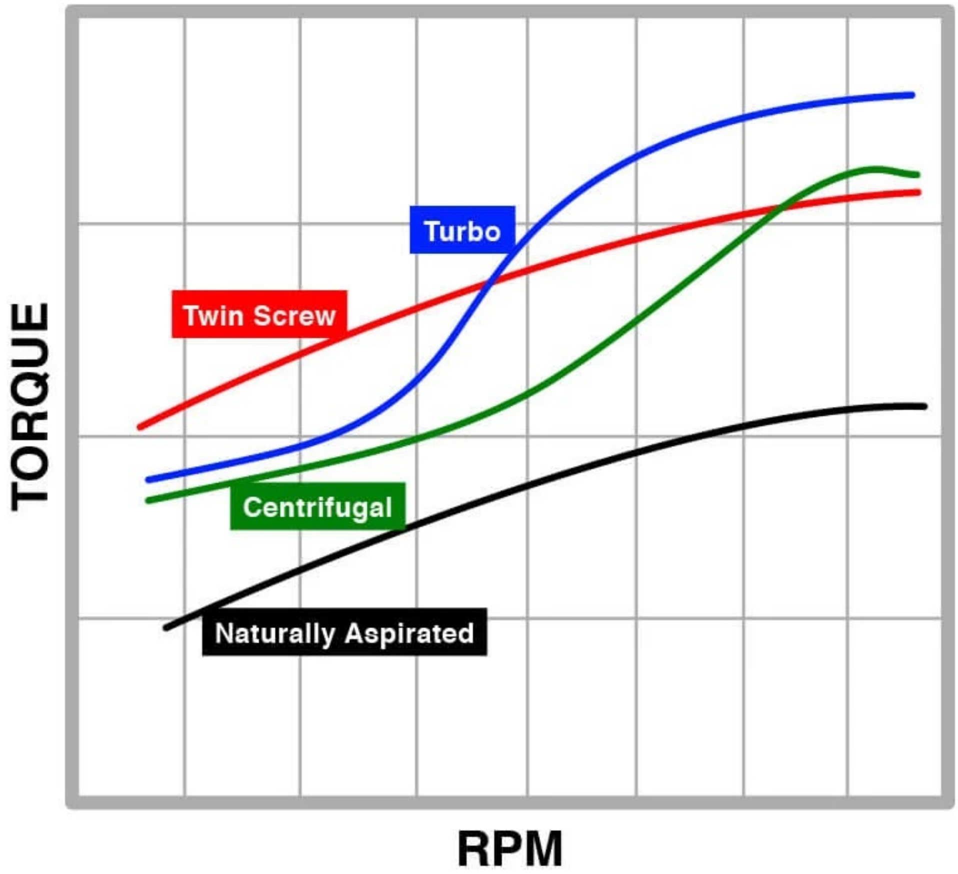


Figure 10: Forced induction comparison graph [30]

As was said earlier, superchargers are mechanically coupled to the crankshaft and therefore deliver boost pressure delayed only by the time required to compress the air in the inlet manifold. Turbochargers are floating free relative to engine speed and require high rpm on compressor to achieve boost pressure resulting in a response lag called turbo-lag, highly dependent on initial engine speed. The higher engine speed is by the start of acceleration the lower is response time of turbocharger. The idea of how different those systems behave is shown in figure 10.

Main advantage of turbocharger is its efficiency, it uses waste energy of exhaust gases to produce boost which would alternatively just end up in the air. Due to the design of a TC it has to be chosen in which engine speed areas, and those areas are relatively narrow, because it's constrained by the map width of the compressor and turbine, the engine will be mostly operated. TC might be designed to work in relatively low rpm as in diesel applications, or it might be designed for some kind of sport application providing high boost at high rpm. In addition, turbochargers require lubrication and for that purpose engine oil is used. Due to the extreme operating temperature it gives extra demand on the oil and leads to faster degradation of it.

Finally, from the drivability standpoint, when driver pushes down the accelerator pedal, the amount of power will not grow linearly and that leads to less predictable behavior of the vehicle. On the other hand, superchargers provide linear boost on a wide range of rpm and driver gets exactly what he wishes, at least with roots or screw type superchargers. They don't require lubrication and are more durable. However, from the efficiency standpoint they take energy directly from the engine which leads to lower efficiency. [6] [7] [2] [1]

4. Electric Boosting System introduction

Downsizing has been proved as quite effective way to reduce CO_2 emissions in passenger cars in everyday use. Big improvements have been achieved in engine efficiency with conventional boosting systems and made 100 BHP per liter of displacement sort of a standard specific power in nowadays cars.

However, these systems have some limitations that have already been mentioned earlier and the foremost are:

- Turbo-lag in case of TC
- Efficiency of mechanical compressors

Considering nowadays hybridization and relatively inexpensive high voltage batteries and electric motors these limitations may be solved by using electrically driven compressors. They give a significant increase of intake air flow, especially at low RPM, with no lag in boosting effect during transients, even at very low RPM.

With increasing vehicle electrification, compact electric motors and batteries it's now possible, to use 48V electrical system which might deliver 4 times more power than 12V (assuming same current).

Additionally, such systems offer greater package freedom within the engine compartment, since no mechanical drive connection is required. The electrical booster together with all the other components needed can be enclosed in a single package, giving also possibility to build up an add-on system to be applied to existing engine units.

System can be designed and set up to couple with existing turbocharger and provide instant boost with no mechanical loses and continue with traditional turbocharger at higher engine speed using waste energy of exhaust gases enhancing efficiency to maximum.

Electrically assisted boosting solves great problem with turbocharged engines, when sizing turbocharger is always a compromise between low-end torque and peak power. With e-boosting its possible to install a big turbocharger, even without variable geometry (VGT) which decreases expenses, providing huge power at high engine speed, keeping great drivability at low RPMs with e-boosting.

Unlike conventional, belt-driven, mechanical superchargers, electronic boosting devices can use power that is generated during vehicle deceleration through electrical brake power recuperation. The degree to which this can be achieved is dependent upon the storage capacity of the battery and whether the vehicle operation provides the opportunity for recuperation events to take place.

There are several concepts and designs of compressor hybridization with their pros and cons, some of them are already placed in production cars whereas other are only concepts. Some of them will be described in next chapter. [9] [10] [11] [12]

4.1. Electrically driven compressor

Electrically driven compressor, commonly known as e-booster, have been studied for many years. The main idea behind that concept is a supercharger driven off by the electric motor. That concept first appeared in 1990's but due to the technology level wasn't anything bigger than a concept. Electrical system of cars at the time was at significantly lower level than it's now. With 12V it was capable of only around 2kW of boost assist power which wasn't enough, however with 48V systems 8kW are achievable. Investigation made by FEV shows hypothetical benefits of e-booster. [10] [12]

Transients

Usage of e-boosting offers significant improvement in transients. Figure 11 shows the potential of e-booster for 12 and 48 V. Graph shows results of simulations for load steps at a constant engine speed for a 2.0 l gasoline engine.

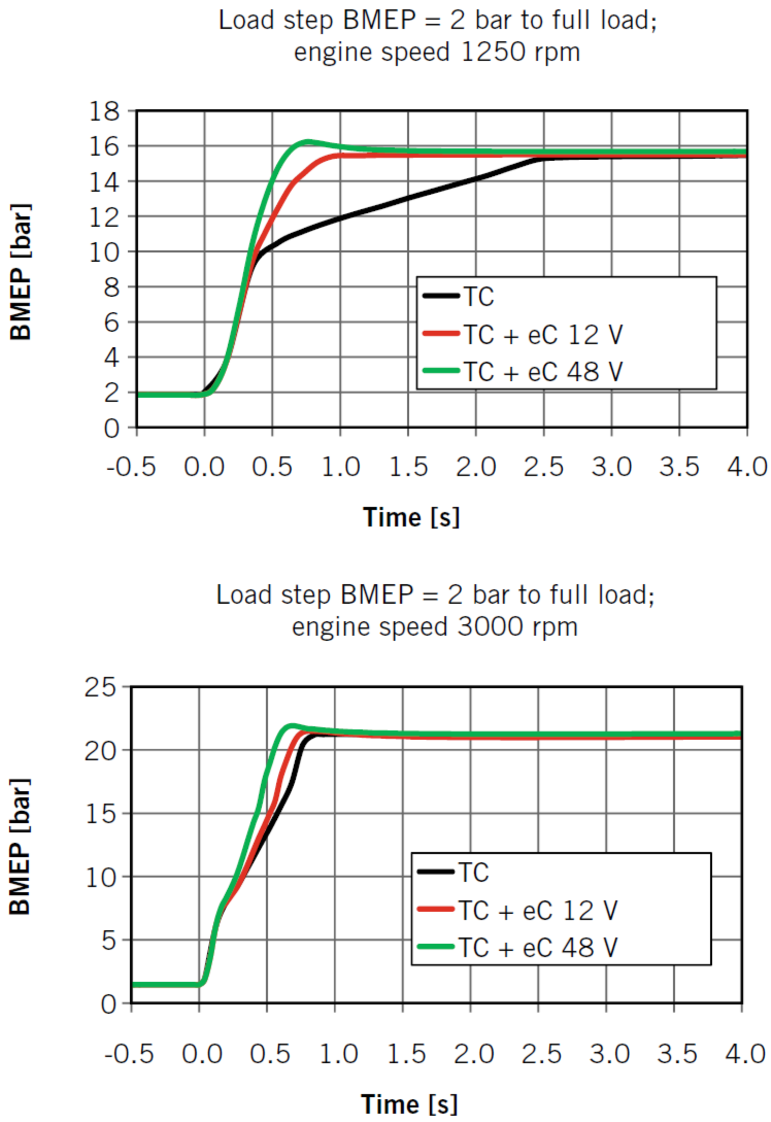


Figure 11: Load steps for a 2.0 l gas engine [12]

E-boosting compensates turbo-lag even in very low engine speeds. 90% of steady-state torque is achieved within 0.4 seconds after achieving NA full load with 12V system or even

0.2 seconds with 48V compared to 1.8 seconds for pure TC. This means, that e-boosting is capable of giving almost same drivability and subjective pleasure as driving large NA engines [12]

Acceleration

Same as load steps, the acceleration is significantly improved. Figure 12 represents simulations of vehicle acceleration from 80 to 120 km/h in highest gear. (reference weight 1600 kg, starting speed n=1480 RPM). As can be seen, difference between 12 and 48 V is low but improvement against pure TC is essential. [12]

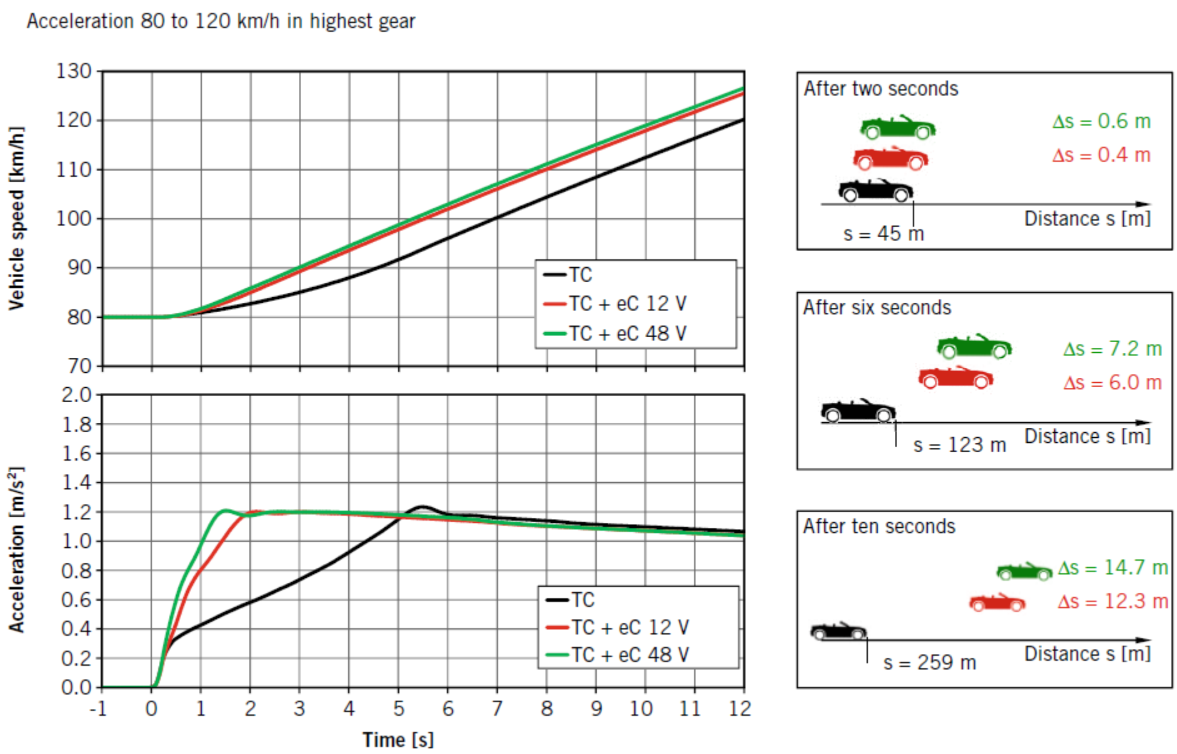


Figure 12: acceleration and speed graph [12]

E-booster and emissions

Electric supercharging has an essential influence on emissions. For diesel engine applications improvement in transient operations is significant. Due to the fact, that NEDC has been replaced by WLTC testing cycle, which consist of 42% of acceleration phases, it's essential to make quicker boost pressure buildup. In that case the in-cylinder air mass is enough to keep soot production low and keep EGR valve open during load steps to reduce NO_x emissions. Figure 13 illustrates benefits of e-booster speaking of emissions. [12]

As can be seen, if e-booster is used, EGR valve can be left partially opened during acceleration. The NO_x concentration peak in the exhaust gas during the load step can thus be reduced by almost 50 % and only slightly exceeds the final stationary value. [12]

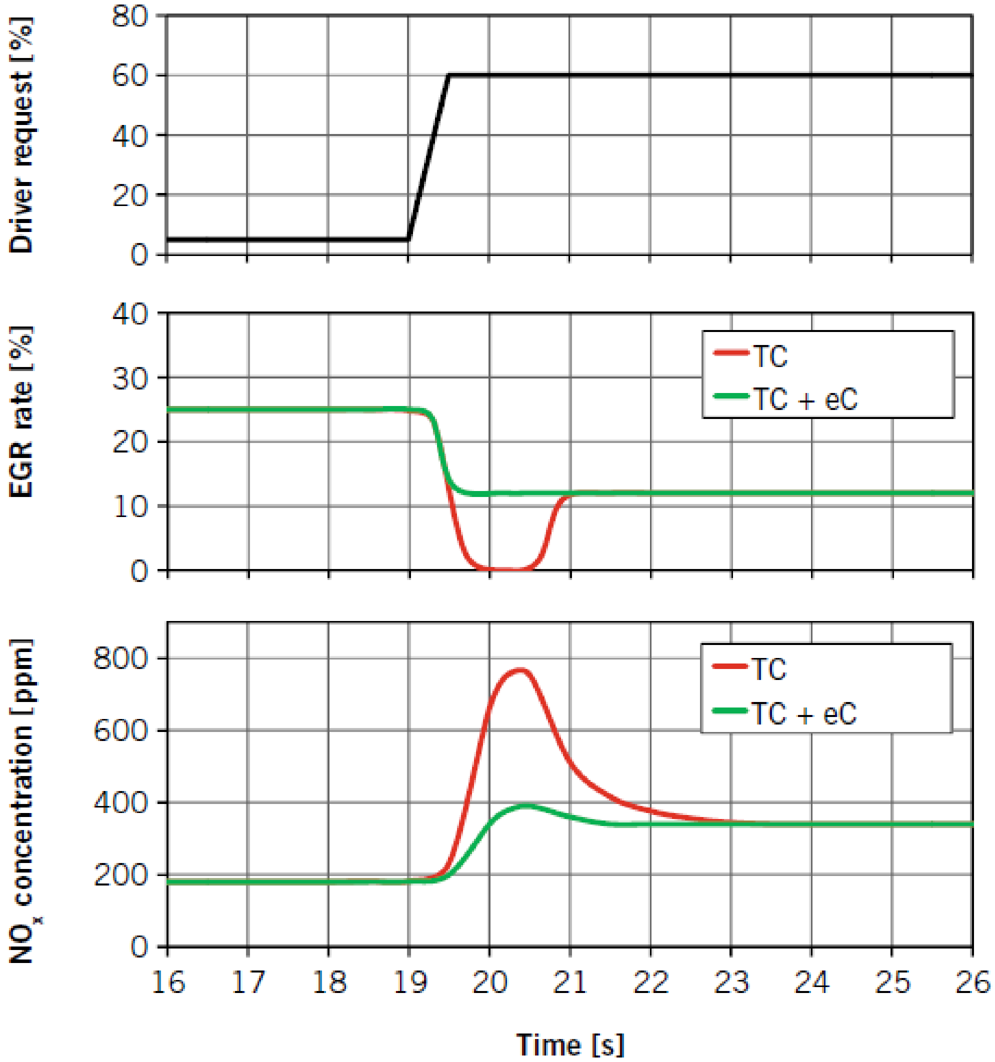


Figure 13: Acceleration process for a diesel engine. The combination of TC and e-booster shows significantly reduced NO_x emissions. [12]

Another important aspect of electrically driven compressors is that without turbine (as in eTrubo), rotor inertia can be kept low, package is more flexible, and no impact on the engine gas exchange is made as there is no backpressure increase, which is a significant advantage, especially for gas engines with tendencies to knock. Considering lack of high temperature impact on device it’s also easier and therefore cheaper to produce. [13] [14]

Considering pros and cons of different types of compressors, it’s better to use centrifugal compressor as an electrically driven one. Main con in conventional application is a lag but since electric motor can get to target RPM very quickly it’s no longer problem though there are lots of benefits of that design like weight reduction, small dimensions and higher pressure at high RPM. [13] [10] [7] [6] [9] [14]

4.1.1. BorgWarner “eBooster ® "

This concept combines conventional turbocharger and electrically driven radial compressor placed on downstream from turbo. Due to the lower boost pressure ratio, the power consumption is lower. The eBooster operates till turbocharger take over and provide more boost. The eBooster can improve transient behavior as it gets to target speed in just a few tenth of a second. Example of design is shown in figure 14.

The eBooster operates in three phases.

- Phase one: Vehicle and engine are running at low load and constant speed, eBooster is inactive.
- Phase two: Driver pushes accelerator pedal – eBooster immediately responds and provides instant boost pressure.
- Phase Three: Turbocharger takes over providing higher pressure than eBooster, eBooster switches off. [10]

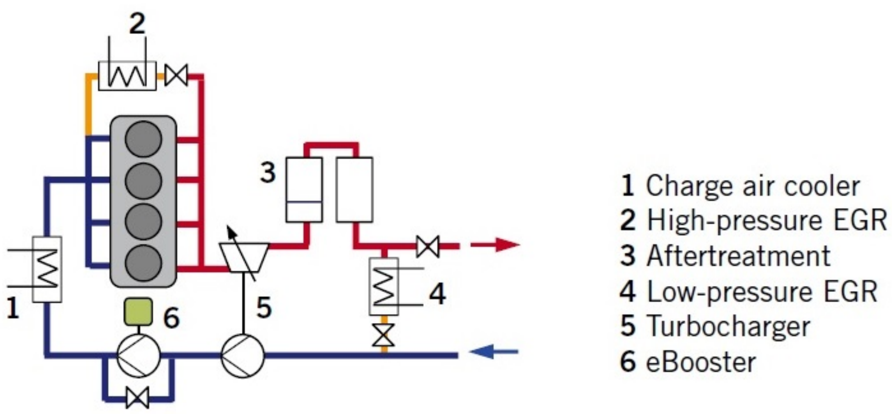


Figure 14: Concept of eBooster placement [10]

4.1.2. Audi SQ7 “electric powered compressor”

Audi SQ7 is the first ever production car with electrical driven compressor. It combines a biturbo concept with electrical radial compressor and belt connected electric motor - alternator. Car’s electric system is working on 48V, electric energy is generated by 3 kW alternator and compressor is driven by 7kW electric motor. It has similarities with BorgWarner eBooster but enhances it with additional turbo and unique variable valve timing mechanism. Concept is shown in figure 15.

Electric powered compressor (EPC) operates again in few phases:

- Phase one: Vehicle stands still and engine is idling. VVT is in low load position, when only one exhaust valve per cylinder is opening. Bypass valve is opened. Compressor is inactive.
- Phase two: Driver pushes accelerator pedal, bypass valve closes and in less then 0.25 of a second compressor spools up to 70.000 rpm and provides boost directly to intake manifold.
- Phase three: engine gets to low-mid RPM, exhaust gases have been built up, bypass valve closes, EPC shuts down and primal turbocharger provides boost.
- Phase three: engine gets to mid-high RPM, VVT is getting to high-load position and each exhaust valve provide gases to its own turbocharger, both turbochargers are providing maximum boost. [15]

Figure 15: Audi SQ7 EPC [15]

4.2. Electrically driven turbocharger

To fulfil the demand on maximizing recovery from residual energy from exhaust gas and to regenerate it in to engine itself or in to auxiliary units in the vehicle another technology based on electrically assisted boosting is used - so called electric turbo compound – ETC.

Considering lots of waste energy in conventional turbocharger it seems to be logical to couple an electric drive to the turbocharger directly on its shaft to recover residual energy of the exhaust gas by replacing wastegate with electric motor-generator, as well as to extend operational boost range of the turbocharger and reduce turbo lag. That concept is becoming attractive, as demonstrated by several studies and by the current application in the F1 racing cars since 2014 championship. [11] [16]

ETC can be designed in different configurations. All of them have its own advantages and disadvantages so let's have a detailed look at them:

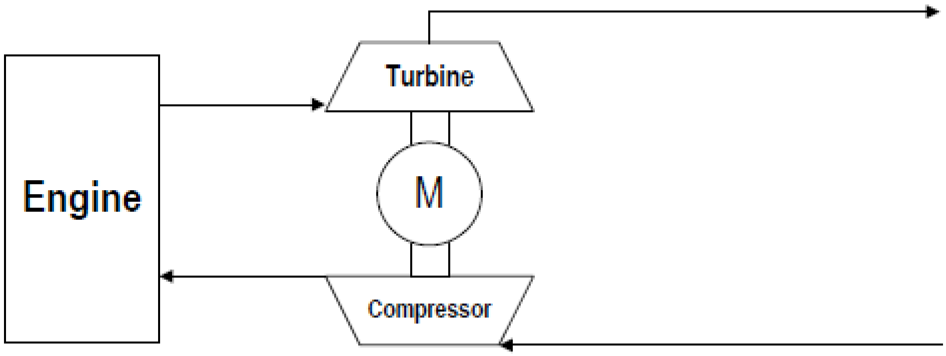


Figure 16: ETC layout 1 [16]

As shown in the figure 16, first layout has an electric motor-generator coupled to the shaft of turbocharger. In this case, when the turbine produces more power than the one necessary to drive the compressor, the excess power is converted into electric power using a high-speed generator incorporated in the TC casing. That design offers advantages in engine downsizing, power increasement and drivability, as the electric unit can work not only as a generator, to harvest excess energy and to slow down shaft and therefore regulate boost pressure, eliminating huge loses in waste gate, but also as a motor, helping to spin compressor wheel in low engine speeds and transients, eliminating turbo lag. Ability to power the shaft also eliminates disadvantage of adding backpressure to engine and increased inertia of a turbocharger. That design has its limitation though. Considering shaft speed and temperature load that configuration puts extra demand on electric unit and requires a completely new design of a turbocharger.

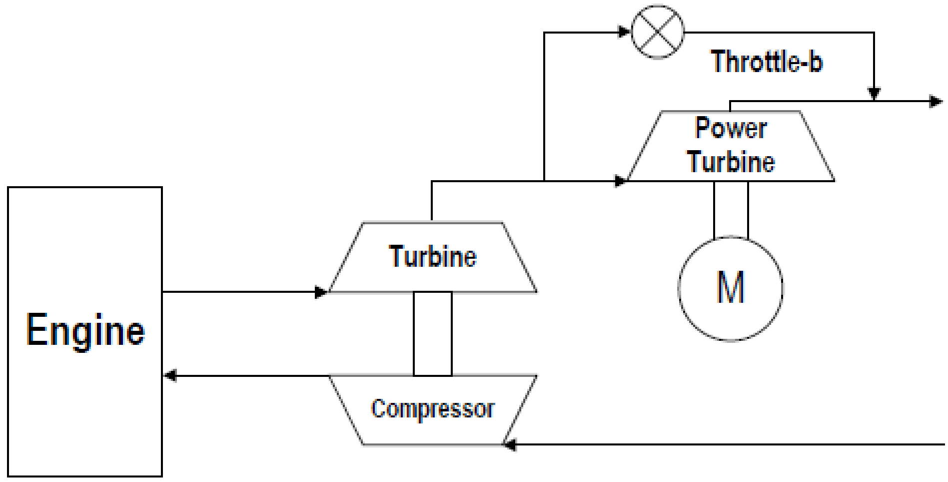


Figure 17: ETC layout 2 [16]

Second option, as figure 17 shows, power turbine may be placed in series on the downstream of the turbocharger. A bypass valve ensures that at low speed and full load power turbine won't affect flow and desirable power will be supplied to the compressor wheel.

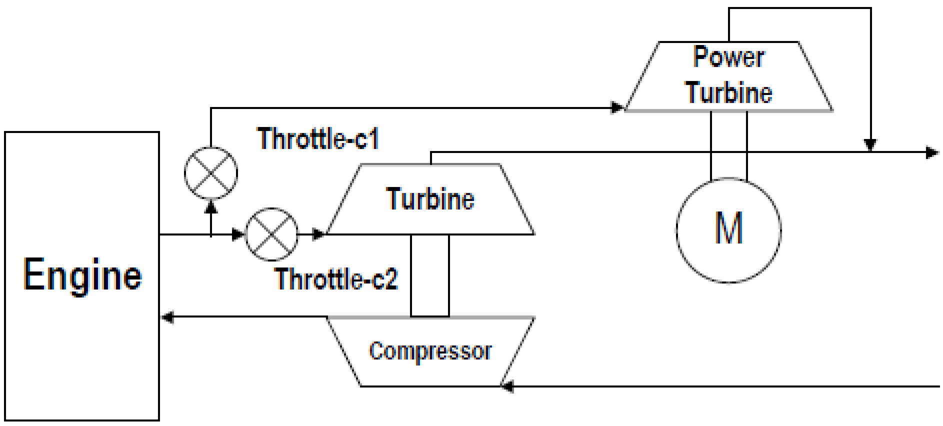


Figure 18: ETC layout 3 [16]

Third layout, shown in the figure 18, improves second one. In that case power turbine is placed in parallel with the turbocharger with two bypass valves which are used to control the exhaust gas flow through turbocharger and power turbine. Wastegate of turbine is unnecessary in that layout, since flow is controlled with bypass valves.

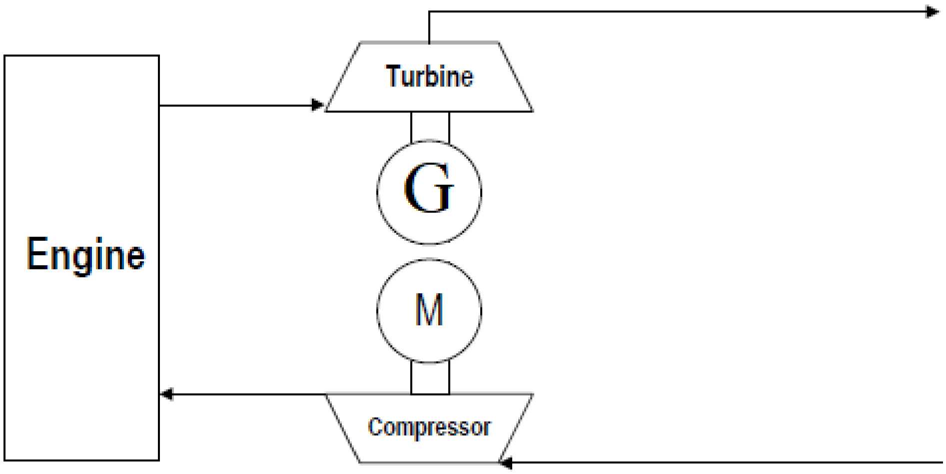


Figure 19: ETC layout 4 [16]

Finally, as can be seen in the figure 19, mechanical connection between turbine and compressor wheel can be replaced with electric bind. Turbine is linked to the high-speed generator, whereas compressor is powered from high-speed electric motor.

Unfortunately, by the time of writing this thesis none of the electric turbos are used in any production car. However, in June 2020 Mercedes AMG announced, that they will use ETC, made in cooperation with Garrett, in near future on variant of AMG's M139 2.0 in-line 4-cylinder engine. That ETC will be probably based somehow on Formula 1's MGU-H, considering the fact that it's Mercedes AMG who is absolutely dominating in that field in F1 Championship since 2014. In addition, in 2021 Mercedes AMG ONE should arrive. Although that kind of sport car can't be really considered as a production car, its powertrain is supposed to be derivative from Mercedes-AMG F1 W07 F1 car, which competed in 2017 World Championship. [17] [18]

4.2.1. Formula 1 "MGU-H"

The only electrically assisted turbocharger is now used in F1 championship. Since 2014 F1 regulations switched from NA 2.4 liters V8 engine to hybrid 1.6 liters V6 engines. Those power units are equipped with the heat energy recovery motor-generator unit (MGU-H) - an electric turbo and the kinetic energy recovery motor-generator unit - a timing gear driven electric motor-generator (MGU-K). These units cooperate and share recovered energy in same battery which means that ETC can be powered with energy recovered via kinetic motor-generator and vice versa. That gives driver opportunity to use extreme power instantly almost all the time. The MGU-K is limited to 120 kW of power, maximum recovered energy to 2 MJ per lap (approximately 4 to 6 km) and maximum deployment of energy to 4 MJ per lap, whereas MGU-H is unlimited. With those systems modern F1 power unit archives maximum power close to 1000 HP still keeping quite good reliability, due to the fact that only 3 power unit components are allowed to use per season which contains of about 20 races, each of 300 km per race plus qualifications and free practices which makes about 7000 km per component at almost full load all the time. [19]

4.3. Partial conclusion

Different designs of electric boosting systems have been discussed. Using CFD simulation it is possible to predict behavior of those systems in different driving modes and get answer to lots of questions, that are still unanswered since those systems still aren't commonly used and there is lack of studies in that field.

The fact that there are only a few production cars[1] coupled with that technology makes doubts about actual economic efficiency and therefore future of it in production cars, since in world where automotive industry is ruled more by marketing managers end economists then by engineers, economical factor is more important than pure engineering. However, it looks like a still perspective technology at least in motorsport application.

Speaking of heavily downsized gas engines main limitation factor is knock and since eBoosting can't help with it, it's questionable whether it's sensible to use eBooster and big TC instead of one smaller TC with VGT.

[1] By the time of writing this work Audi announced that they won't use eBoosting device in next generation of Audi SQ7.

5. GT-suite simulations

In this chapter will be discussed model itself, it's control strategy and simulations – steady-state and transient.

In order to be able to get all necessary information about engine, to make a realistic simulation model, I chose diesel engine from late 90s, since I not only own the car with that engine, but I also have one extra disassembled engine which makes possible to acquire most of necessary dimensions. Turbo diesel by Audi, 2.5L V6, was used in most of D, E and F segment cars by VW on the edge of millennium. Specifically, for purposes of this thesis, I used engine with basic specifications shown in table 1. This engine is known for significant Turbo-lag and poorly matched turbocharger in terms of low-end torque, since full boost pressure is achievable only at 3000 RPM, which makes drivability of that engine not sufficient and eBoosting looks like solution to improve drivability of that car.

Two different models will be compared later. Model with eBooster will be hereinafter referred to as "eBooster + WG TC", Model with VGT Turbocharger as "VGT TC". In some figures and tables results will also be compared to production version of car i.e. Audi A6 C5 2.5 TDI Avant from year 1999 Hereinafter referred to as "Production car" and to Audi A6 C7 45 TDI from year 2018 Hereinafter referred to as "3.0 TDI".

Table 1: Engine specifications

Engine code	AKN
ECU	Bosch EDC15M
Cylinders alignment	V6
Displacement	2496 cm3
Valve timing	DOHC
Compression Ratio	19,5:1
Power	110 kW @ 4000 RPM
Torque	310 Nm @ 2500-3500 RPM
Charge system	VGT turbo charger Garrett GT2052V with vacuum actuation
Intake valve lift	7,9 mm
Exhaust valve lift	6,4 mm

Figure 20: Audi 2.5 TDI engine

5.1. Base engine model

At first stage base engine model was made in GT-Suite. For that purpose, I measured all relevant dimensions on disassembled engine. Detailed 1-D model of intake manifold, exhaust system with simplified catalytic converter and muffler model to simulate backpressure and Wiebe's combustion model calibrated for rotary injection pump based diesel engines were designed. Model map is shown in figure 21. As a next step, data (such

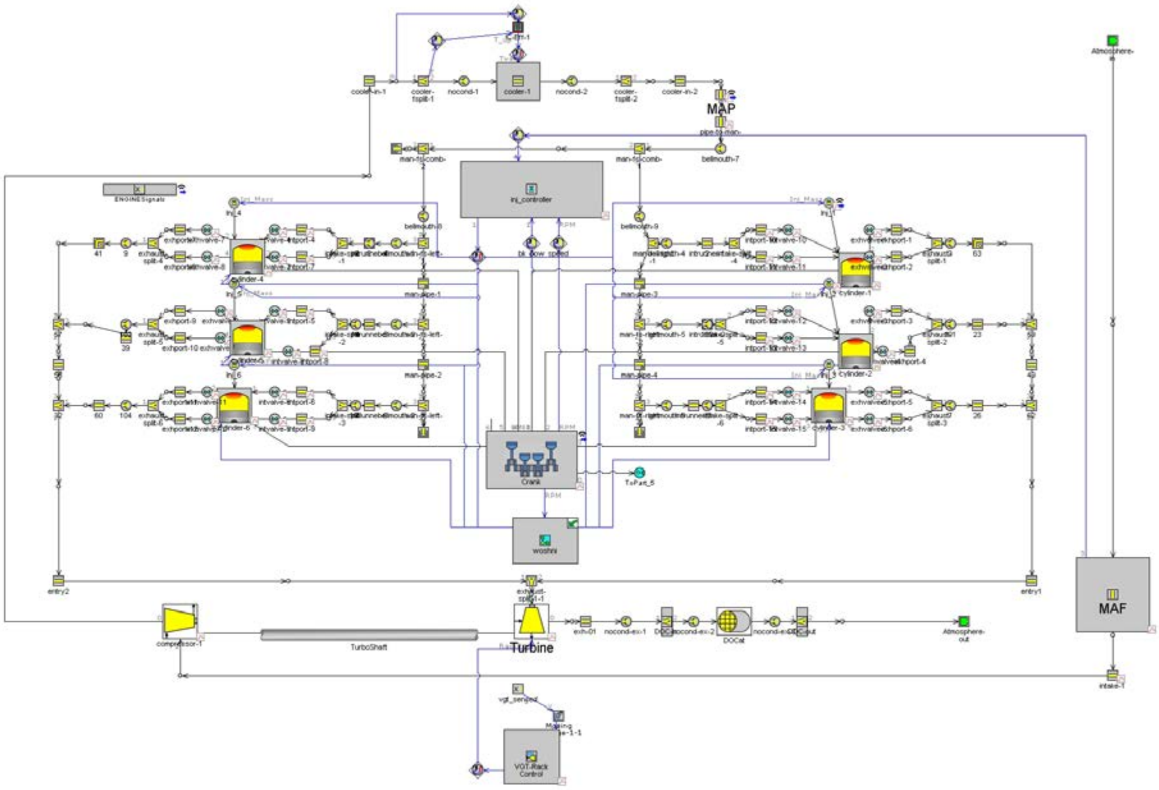


Figure 21: GT-Suite model map.

is boost pressure map, fuel map, driver's wish map, smoke map etc.) from engine control unit were acquired through WinOLS software. Then I made a log through OBD2 diagnostical protocol during test run. On 3rd gear (straight gear with ratio 1:1), car was accelerating from idle to maximum engine speed on straight with no altitude variation. That test run was made as an alternative to measurement on roller brake tester. Among others, this test proved poor low-end torque of engine and lack of pressure at low engine speed (figure 22). Performance map of turbine and compressor from Garrett was also acquired, though due to the trade secret exact values will not be published. With these data I run steady-state simulation tuned model to achieve compliance with reality. Later, map-based regulation was replaced with PID regulators that were tuned to achieve desired values.

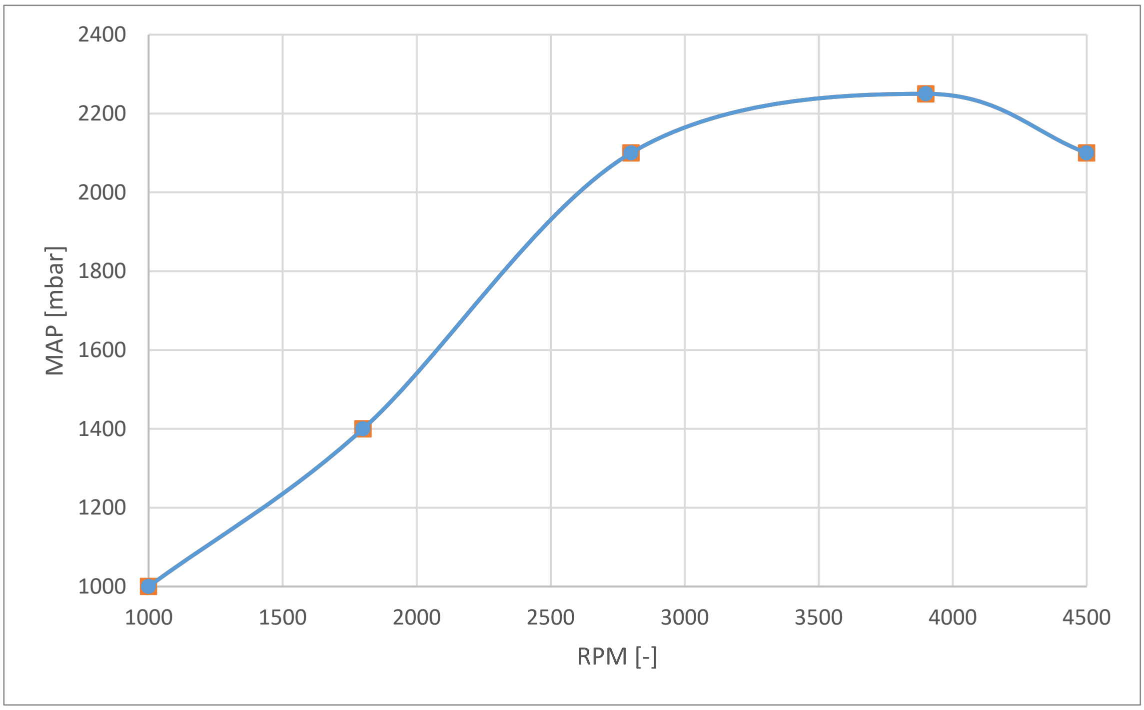


Figure 22: Intake manifold pressure during acceleration from rest

Since discussed engine was developed in mid 90s and power demand was quite low back then, maximum BMEP is only about 15 bar. Considering nowadays demands on passenger cars and fact, that such a low BMEP is a consequence of usage of rotational fuel pump system and related technological and emissions related limitations, new full load characteristic was designed with maximum BMEP of 21 bar which can be seen in figure 25. That power increase is achievable in real engine, since during simulations were considered limitations, such is maximum pressure and temperature in combustion chamber, maximum temperature before and after turbine, capability of intercooler and other essential parameters. It's also known and described in many power-tuning related web resources that, speaking of mechanical durability, engine is capable of achieving 28 bar BMEP. That improvement thou require more modifications to engine such is bigger injector nozzels, modified plungers in injection pump and higher injection pressure etc. However, engine tuning in that way isn't topic of that thesis so it's not going to be discussed further.

Steady state simulations showed that the turbocharger isn't matched well from low-end torque standpoint and does not allow adequate pressure ratio on low speed, due to the surge margin, thou at high speed it is capable to provide more than 3.5 bar. Considering that new full load characteristic was modified according to maximum achievable pressure ratio of compressor in stable area (i.e. bellow surge margin) while keeping lambda over 1.3.

As was mentioned earlier, control of model was made through PID controllers. Injection controller receives actual BMEP and engine speed from the crank and the target load as the accelerator pedal position and injects fuel to meet target BMEP which is prescribed in map shown below (figure 23). VGT system is controlled with GT-Suite's VGT Rack controller based on precalculated pressure map to fulfill turbocharger's constraints (i.e. surge margin, choke and maximum angular speed). Controller receives manifold air pressure signal, engine speed and injected fuel amount and regulates rack position to reach in-map prescribed target pressure.

BMEP/load map											
RPM/%	0	10	20	30	40	50	60	70	80	90	100
800	0	3,1	3,1	3,1	3,1	4	4	5	6	6	6
1000	0	3,1	3,1	3,1	3,3	3,54	4,25	4,95	5,66	6,37	7,08
1250	0	3,1	3,1	3,1	3,11	3,89	4,67	5,45	6,23	7,01	7,79
1500	0	3,1	3,1	3,1	3,76	4,7	5,64	6,57	7,51	8,45	9,39
1750	0	3,1	3,1	3,68	4,91	6,14	7,37	8,59	9,82	11,05	12,28
2000	0	3,1	3,33	5	6,66	8,33	9,99	11,66	13,32	14,99	16,65
2250	0	3,1	3,56	5,34	7,12	8,9	10,68	12,46	14,24	16,02	17,8
2500	0	3,1	3,92	5,89	7,85	9,81	11,77	13,73	15,69	17,66	19,62
2750	0	3,1	4,14	6,2	8,27	10,34	12,41	14,48	16,55	18,61	20,68
3000	0	3,1	4,11	6,16	8,21	10,27	12,32	14,37	16,43	18,48	20,53
3250	0	3,1	4,06	6,09	8,12	10,15	12,18	14,2	16,23	18,26	20,29
3500	0	3,1	4,01	6,01	8,02	10,02	12,03	14,03	16,04	18,04	20,05
3750	0	3,1	3,94	5,91	7,88	9,85	11,83	13,8	15,77	17,74	19,71
4000	0	3,1	3,69	5,54	7,38	9,23	11,08	12,92	14,77	16,61	18,46

RPM /	Target Pressure [bar]											
Inj [mg/cycle]	0	5	10	15	20	25	30	35	40	45	50	51,5
1000	1,00	1,00	1,00	1,00	1,05	1,05	1,05	1,05	1,05	1,05	1,05	1,05
1250	1,00	1,00	1,00	1,00	1,10	1,10	1,10	1,10	1,10	1,10	1,10	1,10
1500	1,00	1,00	1,01	1,01	1,02	1,34	1,35	1,36	1,36	1,36	1,36	1,36
1750	1,00	1,00	1,01	1,02	1,04	1,32	1,62	1,84	1,84	1,84	1,84	1,84
2000	1,00	1,00	1,01	1,02	1,07	1,28	1,65	1,85	2,15	2,33	2,33	2,33
2250	1,00	1,00	1,02	1,05	1,12	1,30	1,57	1,88	2,15	2,45	2,48	2,48
2500	1,00	1,00	1,03	1,05	1,09	1,30	1,57	1,85	2,15	2,42	2,70	2,70
2750	1,00	1,00	1,04	1,08	1,13	1,31	1,56	1,84	2,15	2,40	2,70	2,77
3000	1,00	1,00	1,05	1,10	1,16	1,30	1,56	1,83	2,08	2,38	2,67	2,74
3250	1,00	1,00	1,05	1,12	1,20	1,28	1,54	1,78	2,06	2,33	2,62	2,69
3500	1,00	1,00	1,06	1,14	1,23	1,33	1,52	1,76	2,03	2,30	2,57	2,66
3750	1,00	1,00	1,07	1,15	1,26	1,37	1,49	1,73	2,00	2,27	2,54	2,63
4000	1,00	1,00	1,06	1,15	1,26	1,40	1,53	1,71	1,98	2,24	2,47	2,47

Figure 23: Designed maps

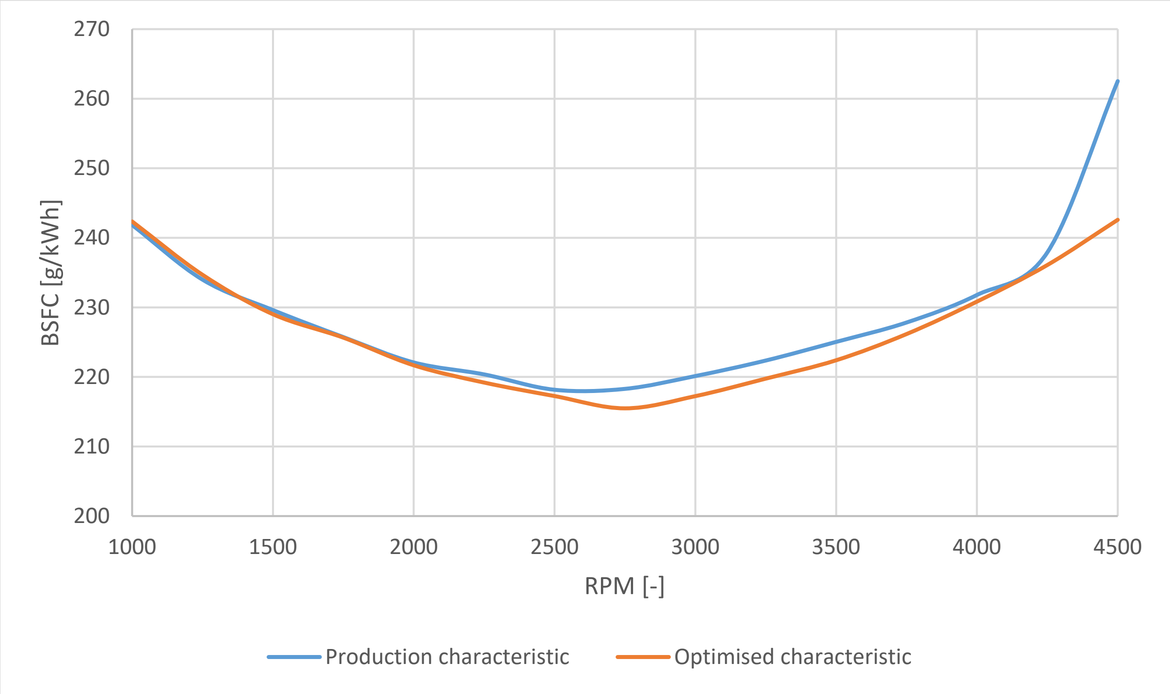


Figure 24: BSFC comparison between production and new designed full load characterstics.

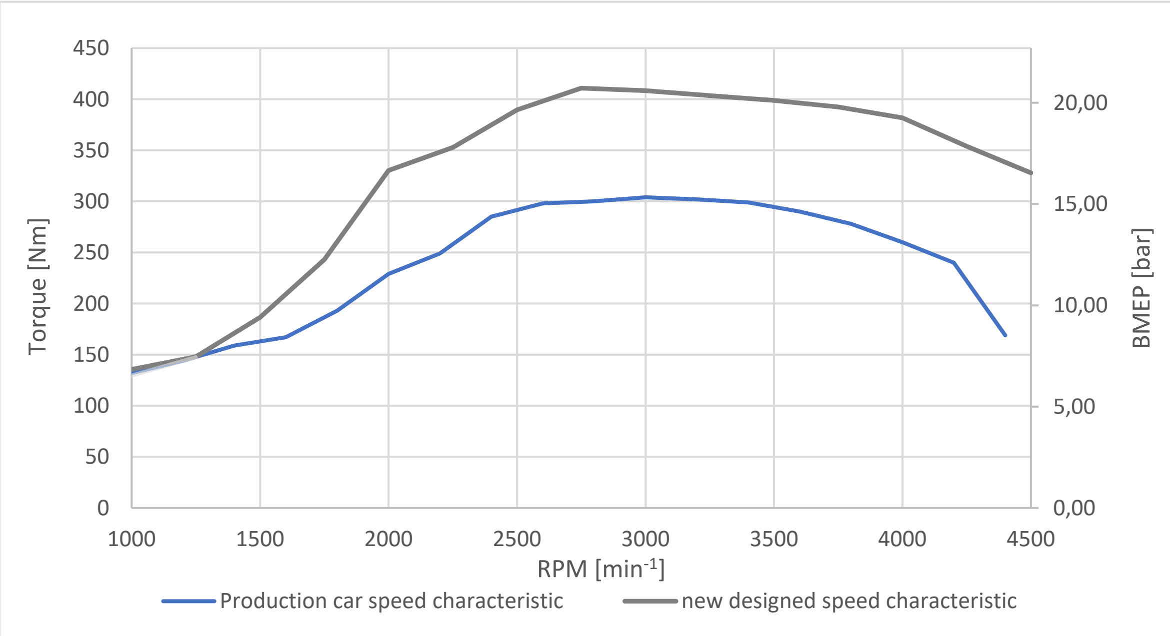


Figure 25: Comparison between full load characteristics.

That resulted in new full load characteristic which is comparable with modern production diesel engines and has slightly better BSFC due to higher BMEP (see figure 25). Later on, this characteristic was used as basis for model with eBooster.

5.2. eBooster model

As the next step eBooster was designed and incorporated into model. Simplified scheme is shown in figure 26. As a design concept was chosen radial compressor situated serially with a by-pass on the downstream from turbocharger.

Compressor performance map was generated with GT-Suite's parametric compressor map template. This template takes the compressor performance data from a single operating point, and generates a fully extrapolated map using a set of physically-based parametric equations. This single operating point (referred to as the design point below) is assumed to be the peak efficiency point on the compressor map, and the inputs at the design point should be specified accordingly. These performance inputs may be specified either using typical performance variables (i.e. speed, mass flow, pressure ratio, and efficiency) or using non-dimensional parameters [20].

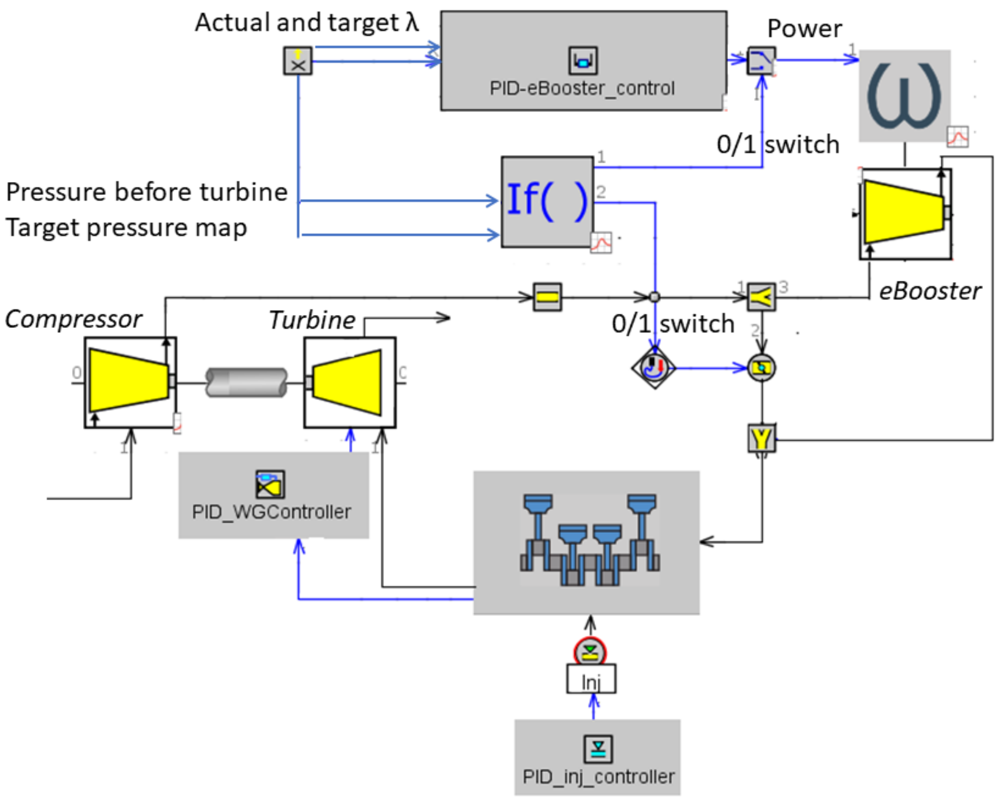


Figure 26: model scheme.

Initial assume was, that eBooster will be helping conventional turbocharger and so target pressure ratio at design point was set to 1.5. Although this assume was fair enough during steady-state simulations, later simulations showed that in transient regimes TC isn't capable to provide even minimal required pressure, so reviewed parameters were set as in table 2 below. Final performance map is shown in figure 27. Then designed external speed characteristic was taken as a basis for a new characteristic for eBooster model. Maximum torque of 410 Nm was kept, but now maximum torque is achieved at 1500 RPM which is significant low-end torque improvement.

Table 2: eBooster parameters.

Compressor Speed at Design Point	50 000,00	[RPM]
PR at Design Point	3,00	[-]
Mass Flow Rate at Design Point	0,05	[kg/s]
Isentropic Efficiency at Design Point	0,90	[fraction]

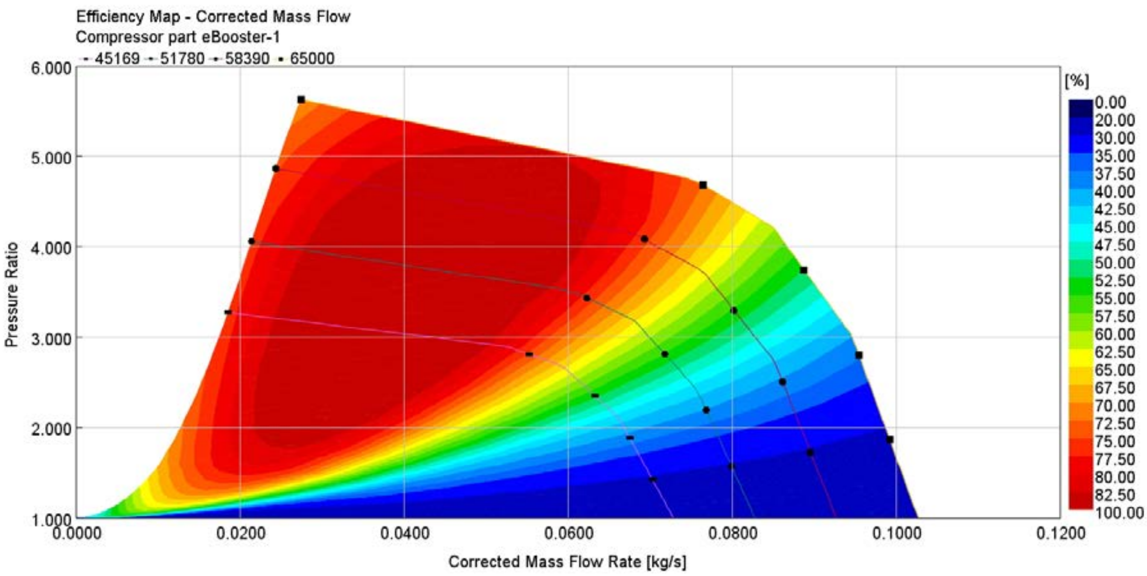


Figure 27: Designed performance map

On the early stages, compressor was driven by boundary speed template which was later replaced with map based 15 kW 48V electrical motor with maximum speed of 120 000 RPM paired with 13 Ah 48 V battery.

Turbocharger was also modified. To achieve, at least hypothetically, lower price of whole system, decision was made to pair eBooster with waste-gate equipped turbocharger. As turbine performance map was chosen VGT based map that corresponds with half opened VGT vanes and scaled by multiplication of mass flow rate by 0.9 to achieve quicker response of turbocharger. Compressor map was also scaled by increasing of pressure ratio and mass flow rate by 10% each. Those modifications actually shift original turbocharger GT2052V closer to its successor GT1756, which was used in next generation of Audi's diesel engine. All that was made to fulfill demand on most wide spectrum of maximum torque.

5.2.1. Control strategy and principals

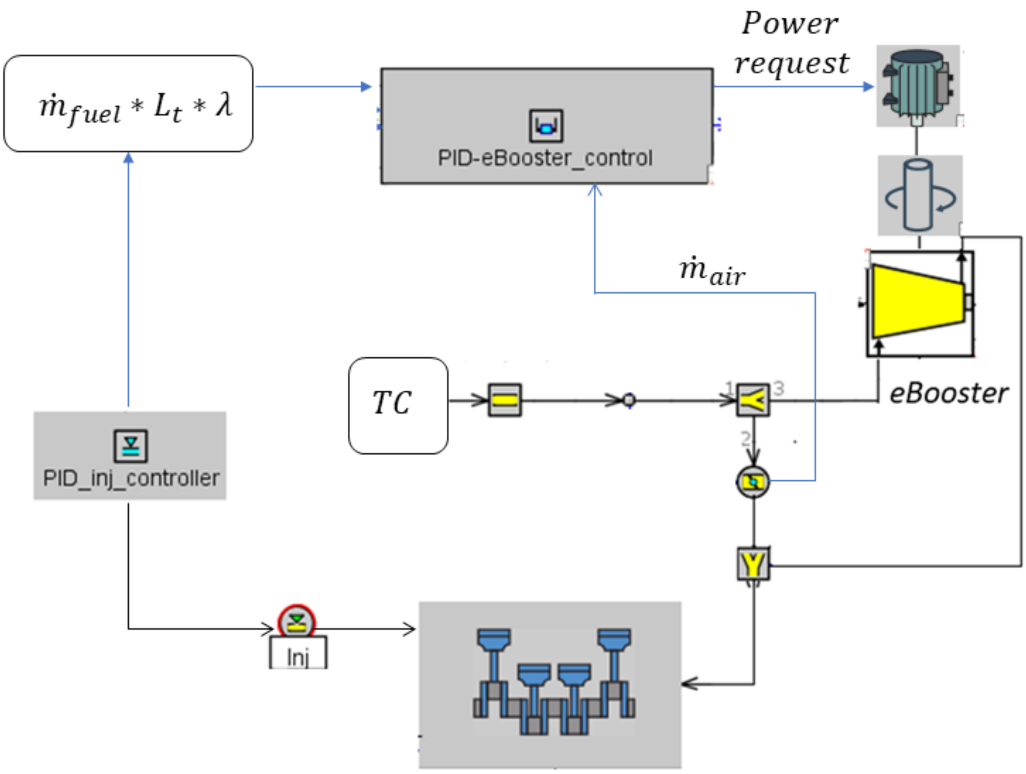


Figure 28: Improved control scheme

During development of model also was designed logical scheme and controlling system. As shown in figure 26, eBooster is controlled by PID regulator. Initial control strategy was based on lambda regulation. PID received signal from lambda sensor and regulated power to electrical motor to reach target air-fuel mixture. Although that worked stable in steady-state regimes in transient simulations became clear, that PID controllers are not working well, when target value is constant. It appears that in transient regime various values changes, but since PID regulator targets constant value it expects those values would come to steaty-stand state either. As consequence PID works in ON/OFF mode which leads to unstable behavior. Due to that change was made (figure 28). As target value to eBooster controlling PID comes instant value of mass flow rate of injected fuel multiplied by stochiometric coefficient of 14.5 and multiplied by target lambda of 1.3. That value is actual required air mass flow to reach demanded air-fuel mixture. As input to PID comes signal from MAF sensor and as output power request to electrical motor.

Another aspect of regulation strategy is actual actuation of eBooster and whole controlling system. That was made through if-then condition based on Rateau equation (2). Rateau equation shows relation between pressures before and after turbine and compressor.

$$(2) \qquad \frac{p_{T2}}{p_{T1}} = \left\{1 - \frac{\dot{m}_C}{\dot{m}_T}\frac{c_{pC}}{c_{pT}}\frac{T_{K1}}{T_{T1}}\frac{1}{\eta_{Ts}\eta_{mTD}\eta_{Ks}}\left[\frac{p_{C2}}{p_{C1}}^{\frac{\kappa_C - 1}{\kappa_C}} - 1\right]\right\}^{\frac{\kappa_T}{\kappa_T - 1}}$$

Hence, it’s possible to assume that for turbocharger to work it’s required that pressure before turbine is higher than target pressure in intake manifold.

If-then condition works on that principle. Map of required air pressure was precalculated for designed speed characteristic. Figure 26 gives basic idea of control principle. 2 input signals are sent to If-then element: pressure before turbine and actual target intake pressure from map. If required pressure is higher than actual pressure before turbine then signal from eBooster PID is sent to electric motor, by-pass valve in manifold and waste-gate on turbocharger closes and WG PID is deactivated. Otherwise value from eBooster PID is overwritten with 0 sent by if-then element and eBooster circuit is closed.

5.2.2. Troubleshooting

During simulations various complications occurred. Some of them were mentioned before, others will be discussed here. Significant complication was related to eBooster PID gain tuning. Due to highly inconsistent states during different simulations, or even during one transient simulation, it's nearly impossible to set one gain value for entire simulation. For that reason, active elements, through which it is possible to impose gain values during simulation runtime, had to be implemented into model. As it showed up, PID regulators aren't optimal solution for transient simulations and for the future it's better to use map-based model.

Another complication was related to generated performance map of the eBooster. As it showed up later, generated map isn't sufficient to fulfill all demanded area with adequate efficiency due to quite wide spectrum of eBooster activity. For that reason, it took numerous iterations to find somehow sufficient solution.

5.2.3. Possibilities of future model usage

Discussed model was made with modular principles, which means that most of its elements are parametric and might be adjusted for any other diesel engine. It's not limited only to WG controlled turbocharger, since there are controllers for both WG and VGT. It's also possible to quickly change target for those controllers in case set up, whether it has to be target boost pressure, BMEP or A/F mixture. For that reason, it might be used in future simulations of different engines to evaluate possibility of using eBoosting technology. With this said, thesis led to development of whole method of eBooster implementation to an existing engine, though not all the aspects have been considered which leaves space for future improvement.

5.3. Steady-state simulation

Steady-state simulations for comparisons of two variants were made to prove basic principals and benefits of eBoosting and set up models to achieve compliance with real life. As was written before, first variant was equipped with conventional turbocharger with VGT and the second one had turbocharger with waste-gate and eBooster. EBooster was designed to be operational only at low engine speed - from idle to 2500 RPM. As can be seen in figure 29 eBooster offers target pressure from very low engine speed which also allows to match turbocharger for peak-power operation. As a consequence, it offers wide spectrum of torque which is essential for good drivability.

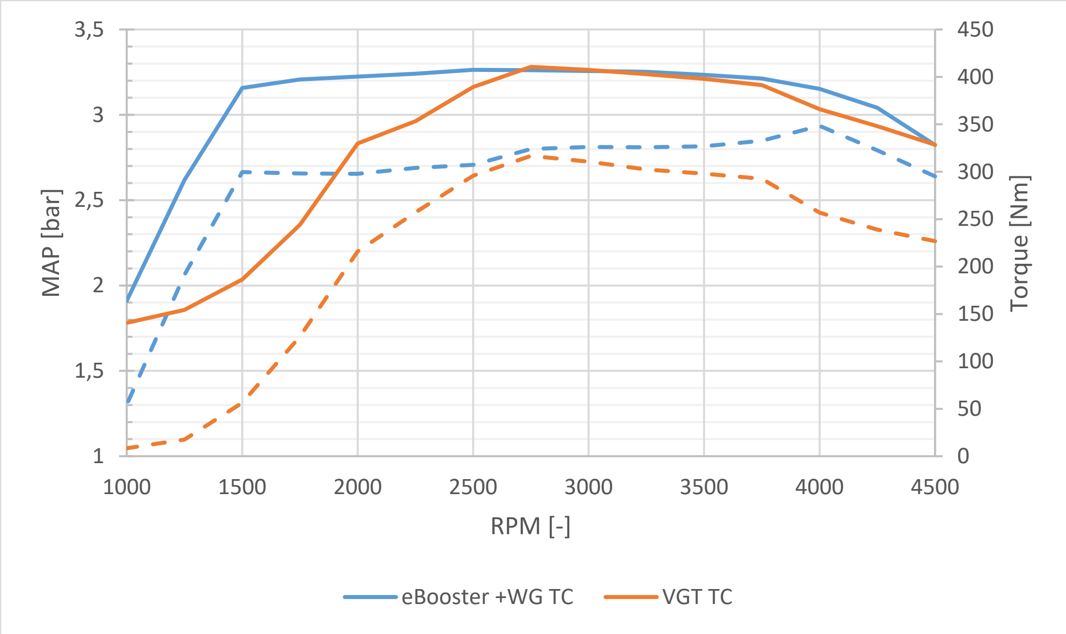


Figure 29: comparison between eBooster and VGT TC. Dashed lines represent pressure, continuous lines represent torque.

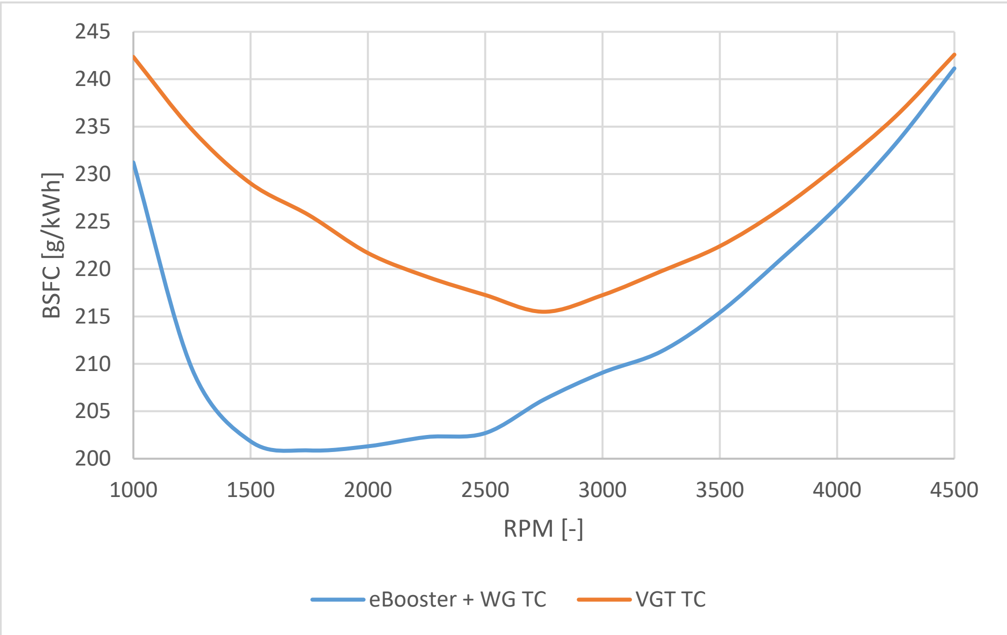


Figure 30: BSFC comparison

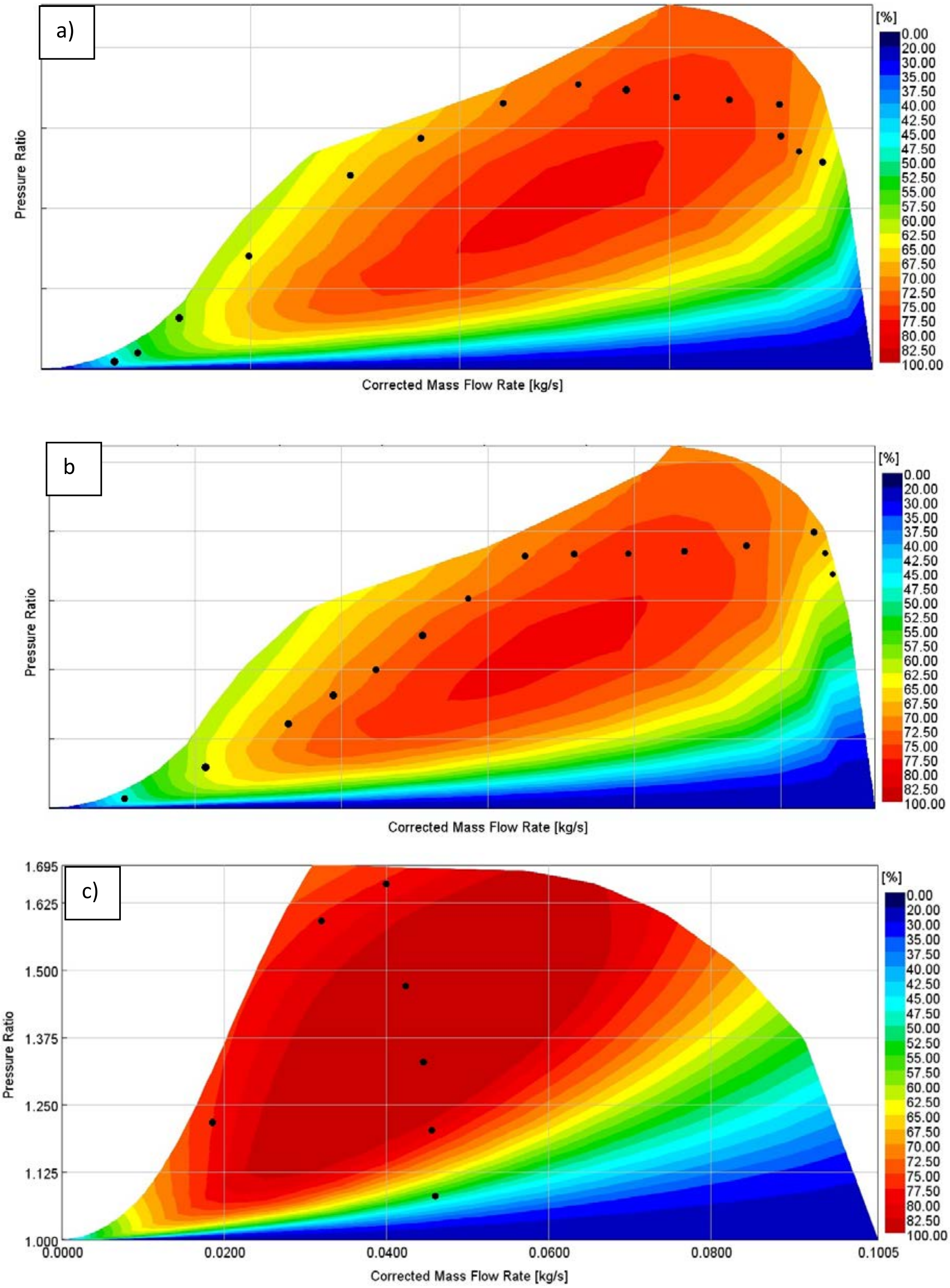
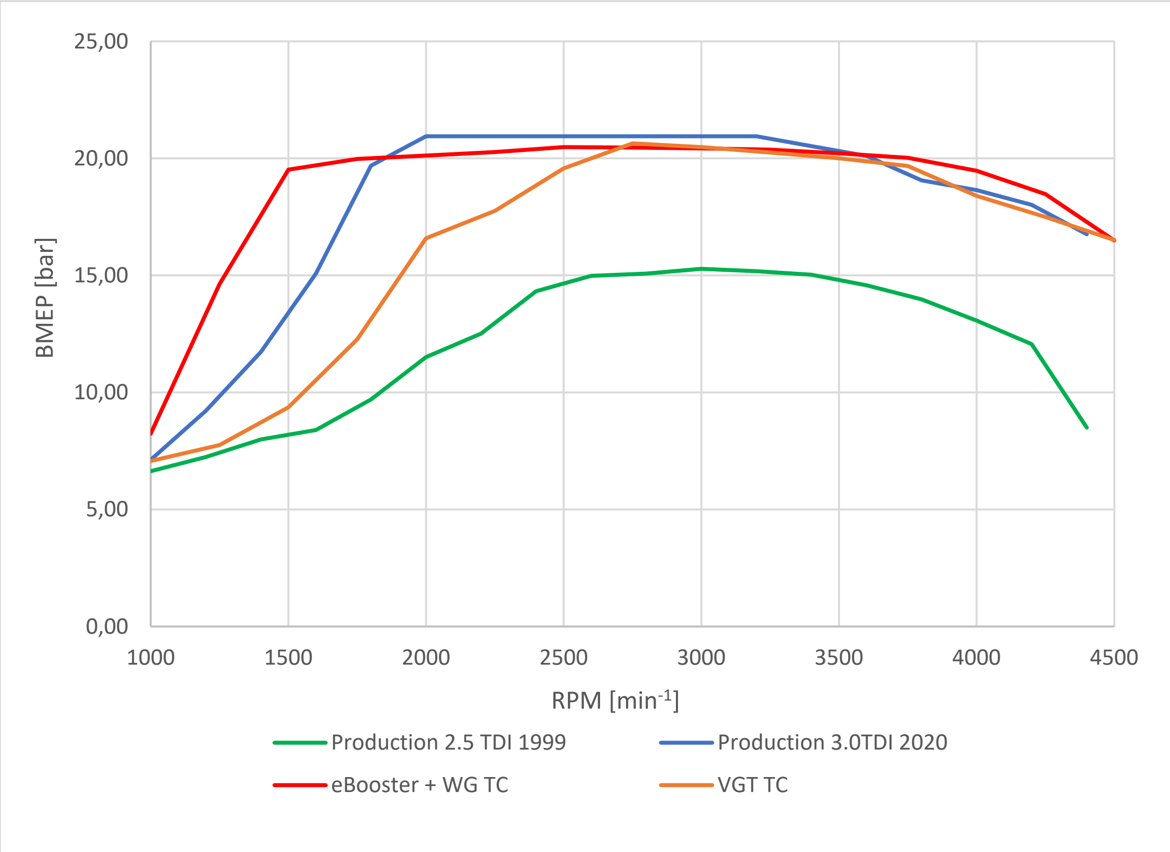


Figure 31: Compressor efficiency maps during simulation of external speed characteristic. a) TC map without eBooster, b) TC map with eBooster, c) eBooster map



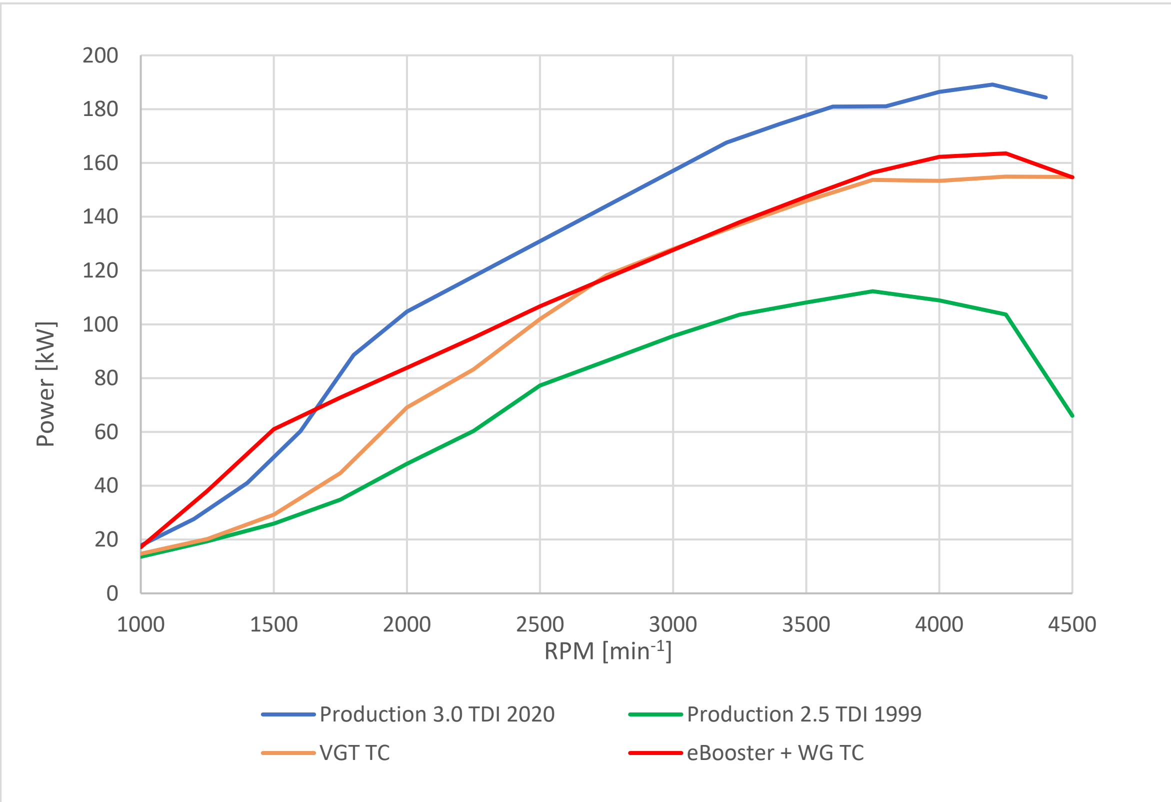


Figure 32: Full load characteristic comparison

Another benefit provided by eBoosting is moving operating points away from surge line. This is shown in figure 31. In case of external speed characteristic for conventional turbocharger efficiency map shows[2], that it operates as close to surge margin as possible, thou it's not sufficient to provide good drivability due to low torque at low speed. On the other hand, eBooster keeps operating points on a safe distance from surge line while offering high pressure and as a consequence high low-end torque and great drivability.

As shows figure 32 eBooster offers significantly higher low-end torque than turbocharger of older construction with vacuum actuated VGT but also develops brings target torque quicker and in wider spectrum than modern electrically actuated VGT in case of Audi's 3.0 TDI.

Due to higher BMEP at low engine speeds, BSFC is also significantly improved as shows figure 30. Lowest specific consumption is also moved to lower engine speeds which is beneficial in urban driving cycles. Figures 36 and 37 shows BSFC calculated for full speed characteristic of both models.

For both variants was run optimization to find optimal injection timing. Injection timing has essential effect on engine efficiency and consequently BSFC. The higher is injection advance the lower is BSFC. On the other hand, due to the fact that the peak of combustion is moved closer to the TDC also pressure and temperature in combustion chamber rapidly increases. For those reasons it's necessary to find balance and optimal solution. Results of pareto optimalisation led to values that were somehow expected – in low-speed injection is retarded for 2° after TDC but with growing speed injection advance grows to 8° before TDC.

In addition, simulation of full speed characteristic was made for eBooster variant. Results are given in figures 33, 34 and 35 bellow.

[2] Due to trade secret of Garrett values of compression ratio and mass flow rate are not published.

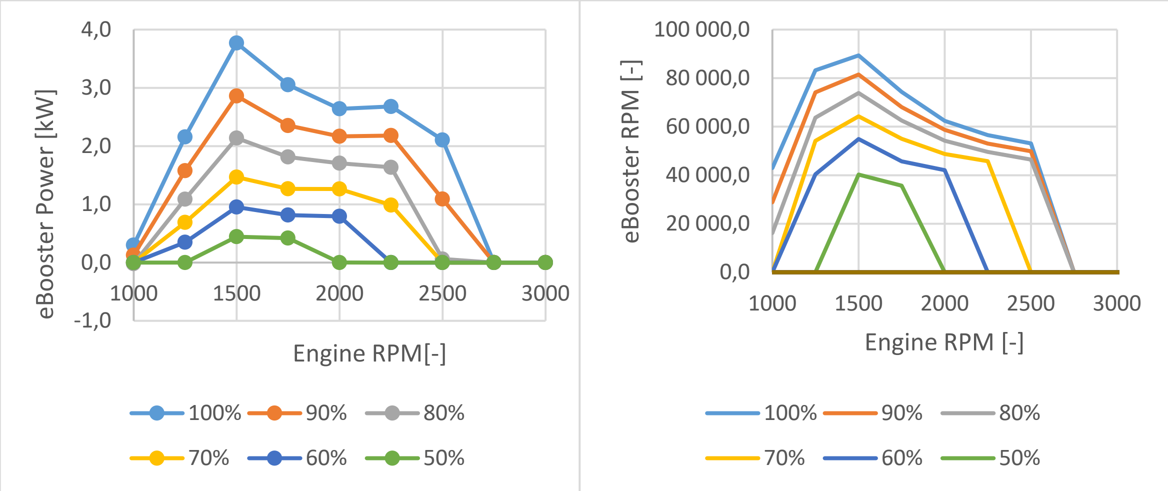


Figure 34: eBooster speed and power at different engine load at steady-state.

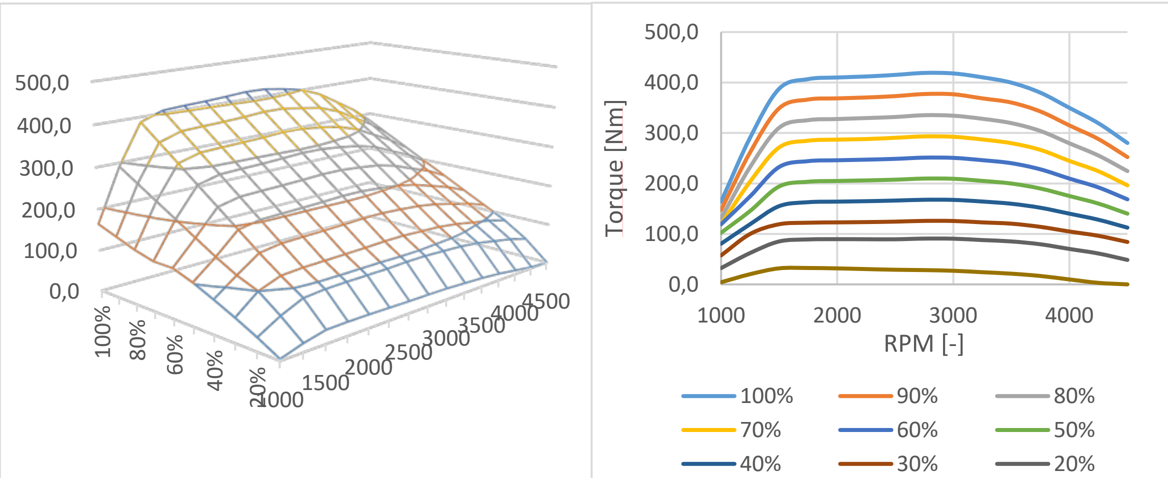


Figure 33: Full speed characteristic eBooster +WG TC.

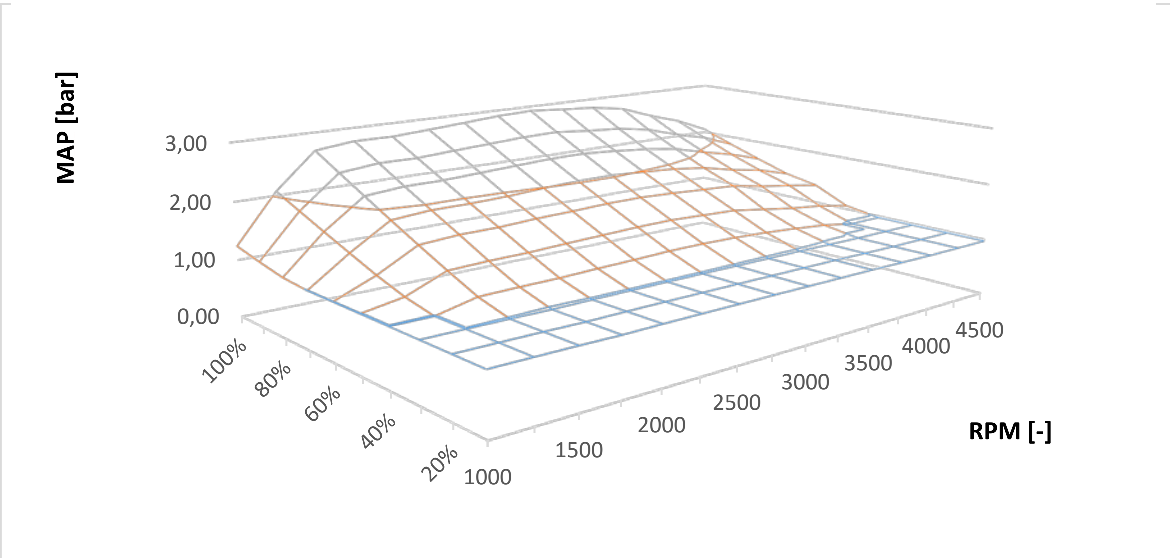


Figure 35: Pressure map for different engine speed and load.

RPM	BSFC [g/kWh]								
	100%	90%	80%	70%	60%	50%	40%	30%	20%
4500	246,7	247,9	250,9	255,0	261,0	267,4	271,5	289,6	362,9
4250	239,2	239,6	241,9	245,1	250,2	257,2	262,0	273,5	317,2
4000	232,5	232,0	233,9	237,0	241,4	248,0	256,2	263,0	293,2
3750	226,9	225,6	227,3	229,8	233,7	239,5	247,8	253,6	274,5
3500	220,6	220,4	222,2	224,5	228,1	233,3	241,3	246,9	263,6
3250	215,8	216,4	218,2	220,5	223,9	228,8	236,5	242,7	256,9
3000	212,6	213,3	215,0	217,2	220,5	225,1	232,5	239,0	251,2
2750	210,5	211,5	213,0	215,3	218,4	222,9	229,8	236,4	247,9
2500	208,7	210,2	211,8	214,1	217,1	221,5	228,2	234,1	244,9
2250	207,7	209,3	210,6	212,0	214,3	220,6	227,3	232,7	242,3
2000	205,6	207,3	209,6	210,4	211,8	220,1	226,7	231,6	239,7
1750	204,0	205,8	208,2	211,1	213,7	220,4	226,9	231,5	238,9
1500	204,4	206,3	208,7	211,8	215,8	219,3	228,8	232,9	239,5
1250	211,2	213,8	217,1	221,3	226,8	233,6	236,3	238,0	254,9
1000	232,0	236,1	241,6	241,4	241,4	241,2	244,7	257,8	305,2

Figure 36: BSFC values for full speed characteristic of eBooster + WG TC

RPM	BSFC [g/kWh]								
	100%	90%	80%	70%	60%	50%	40%	30%	20%
4500	242,6	241,6	244,0	246,6	250,3	257,4	272,4	310,7	480,7
4250	236,1	236,1	238,7	242,6	245,3	250,7	262,5	292,2	413,0
4000	230,8	231,5	234,0	238,1	241,5	245,7	254,5	277,2	364,9
3750	226,2	227,3	229,7	233,2	238,7	241,7	247,7	263,9	325,4
3500	222,4	224,0	226,5	230,1	235,3	240,2	244,6	257,5	307,7
3250	219,8	220,8	223,1	226,6	231,7	239,3	242,4	252,0	292,4
3000	217,2	218,2	220,0	222,9	227,3	234,4	239,6	246,5	279,2
2750	215,5	216,2	217,8	220,5	224,2	230,3	237,7	242,1	268,5
2500	217,3	217,8	218,1	219,6	223,1	228,9	235,9	239,7	264,8
2250	219,2	219,7	220,5	221,4	223,7	230,0	234,1	239,0	266,5
2000	221,7	222,2	222,4	222,8	224,7	231,2	232,5	237,8	266,0
1750	225,7	225,7	226,2	227,8	233,3	232,5	235,4	248,2	297,7
1500	229,0	229,5	232,2	233,0	233,3	236,5	245,7	270,8	364,8
1250	234,7	235,7	235,5	235,9	238,2	244,3	258,2	293,3	431,5
1000	242,4	242,8	242,4	243,4	246,6	253,7	269,2	306,0	454,4

Figure 37: BSFC values for full speed characteristic of VGT TC

5.4. Transient simulations

For transient simulations simplified model of vehicle was created – Audi A6 C5 FWD paired with manual 6 speed gearbox. All characteristics were taken from catalogues (gear ratios, curb weight, aerodynamics etc.). Main controlling element is "Driver" - preset PID controller which imposes "accelerator pedal" as value of engine load, "clutch pedal" and "brake pedal" which is then sent to engine control PIDs. "Driver" also initiates car launch procedure. Engine itself is operated in load mode in that scenario. Detailed engine model is hidden in sub-system "ENGINE" as shown in scheme bellow (figure 38). Sub-system vehicle contains suspension and body elements and element transmission contains model of gearbox. Parameters of simulated vehicle are shown below.

Table 3: Vehicle parameters

Wheelbase	2760	mm
Length	4800	mm
Width	1810	mm
Height	1450	mm
Aerodynamic drag coefficient	0,28	-
Frontal area	2,19	m^2
Curb Weight	1600	kg
Body style	Wagon	-

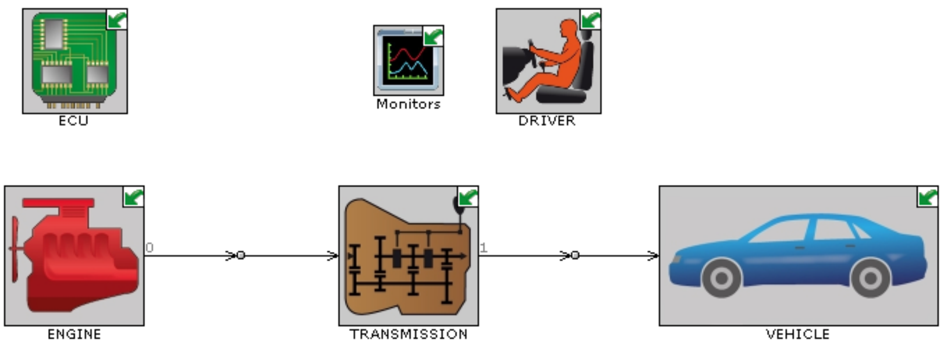


Figure 38: Scheme of transient simulation model.

5.4.1. Acceleration from rest

As first transient simulation was chosen acceleration from rest. For that simulation eBooster PID gains had to be changed since boundary conditions are different comparing to steady-state simulations. Gear shifting strategy was also adapted to reach quickest acceleration – gears are shifted at almost engine speed limit.

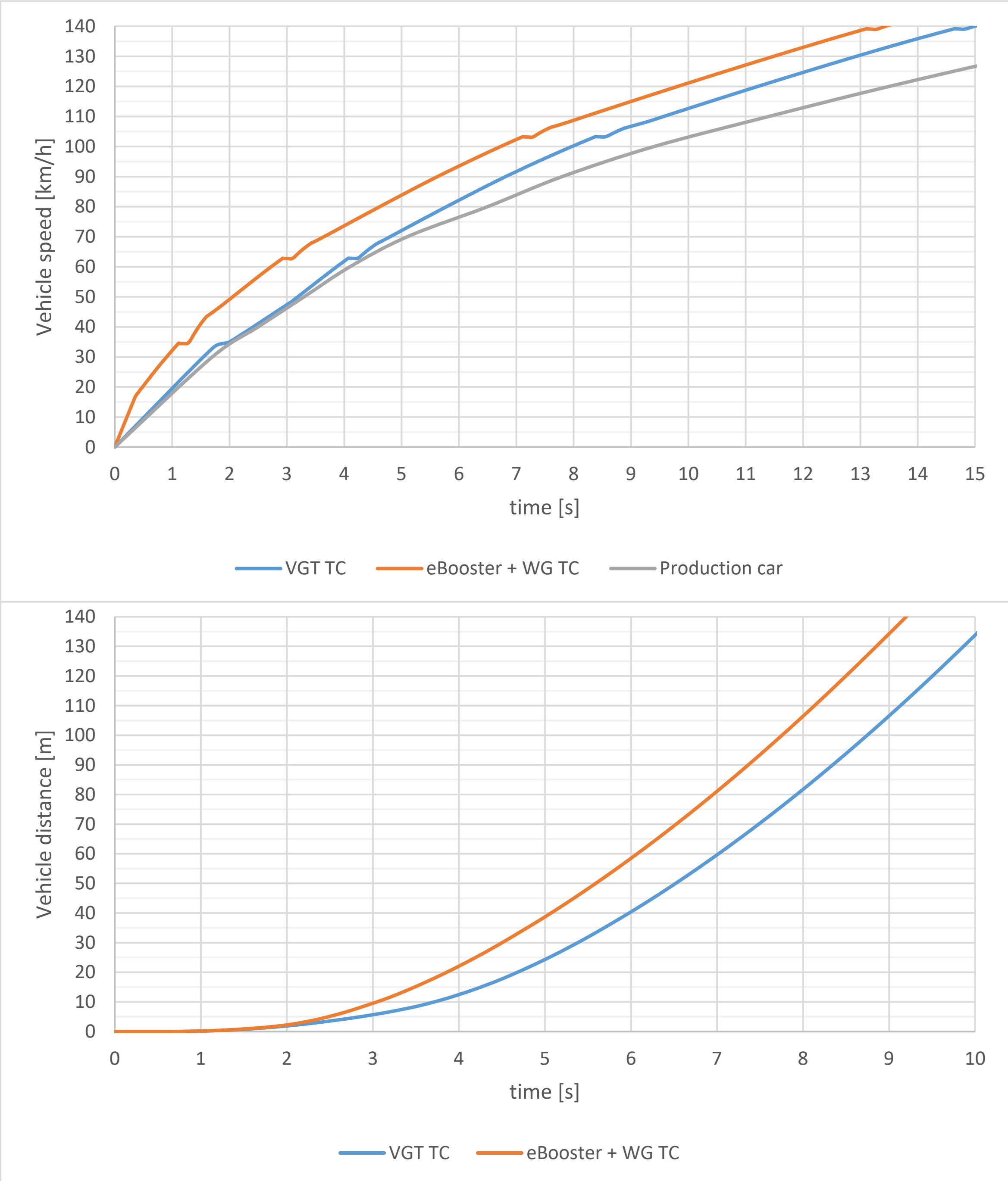


Figure 39: Comparison of acceleration progress.

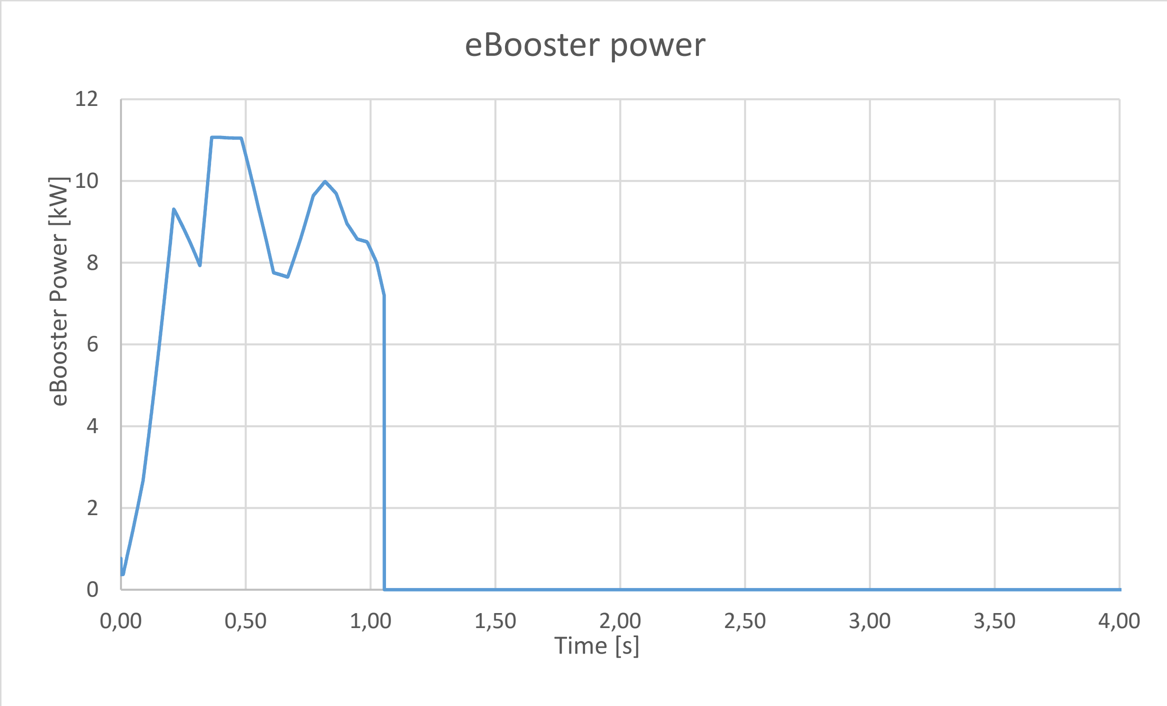


Figure 40: Electrical power retrieved from battery during acceleration.

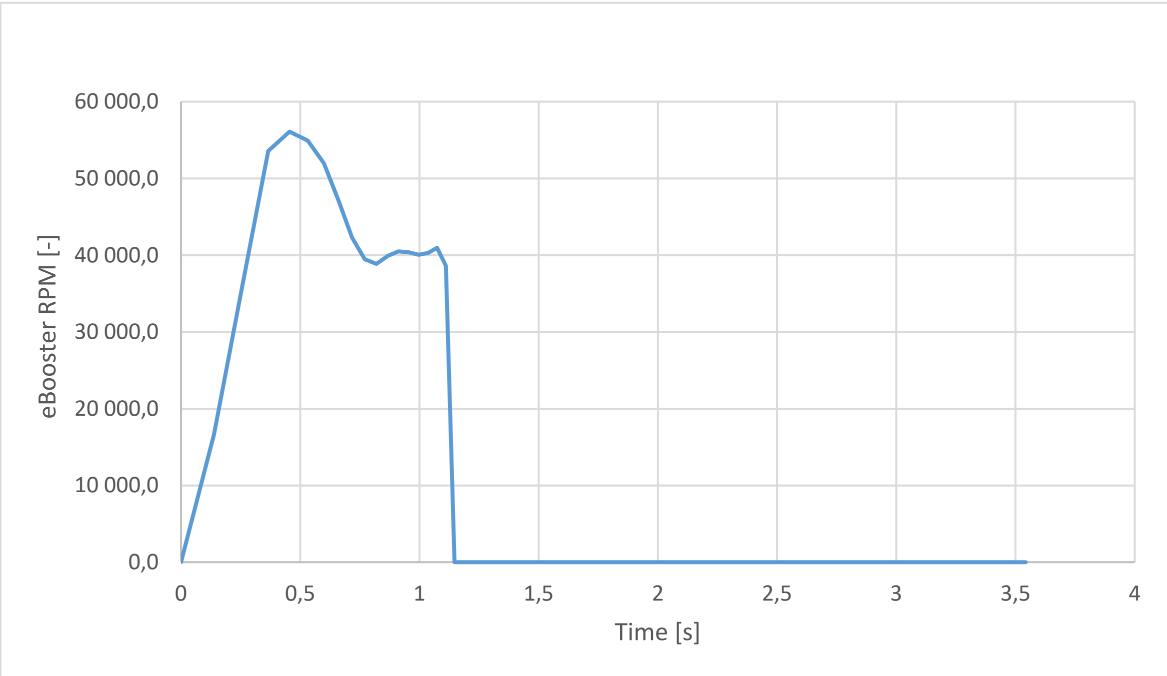


Figure 41: eBooster angular speed during acceleration.

As can be seen in figure 39 vehicle dynamic was improved significantly with acceleration time to 100 km/h in less than 7 seconds which is more than second less than in case of conventional VGT turbocharger and more than 3 seconds less comparing to production version of car regarding to catalogues. Exact acceleration times are shown in table 3 below. Acceleration times achieved with eBooster are lower than in modern turbo diesels in that segment thou nowadays 3.0 l displacement is standard. For example, 2018 Audi A6 45 TDI with 3.0 TDI reaches 100 km/h in 7.1 second while it has better aerodynamics and quick shifting double-clutch gearbox S-Tronic®.

Table 4: Acceleration times in seconds.

		VGT TC	eBooster	Production car
Time to Speed	50 km/h	3,2	2,0	3,3
Time to Speed	100 km/h	8,0	6,7	9,4
Time to Speed	150 km/h	17,4	15,7	21,7
Time to Speed	200 km/h	37,0	34,2	66,4

As it was foreseen eBooster in that scenario is used only in the very beginning of acceleration for about one second. However, requested power is significantly higher in transient than in steady state and as shown in figure 36 reaches maximum of 11kW of electrical power. Nevertheless, instantaneous current at battery terminals never exceeded 300 A which is considered to be reasonable limit in modern Li-Ion batteries.

5.4.2. Dynamic acceleration tests

Next test involved acceleration from 60 km/h to maximum speed at 5th and 6th gear and also shows significant improvement in vehicle dynamics. Those regimes occur often on highway when driver needs to instantly accelerate. In case of automatic gearboxes so-called “Kick-down” helps, however there’s always a gap till gearbox reacts and even thou engine speed will increase, it still takes time for turbocharger to get to demanded angular speed. eBooster seems like sufficient solution since it show great improvement in that field as shows figure 38 with selected exact values in table 4. Simulations showed impressive results. With eBooster at 6th gear vehicle dynamics is comparable with 5th gear with conventional VGT. However, it’s predictable that with down-shifting eBoosting advantage lowers, since engine speed gets higher. Nevertheless, acceleration is almost linear which results in great drivability and, what’s very important for safety reasons, predictable

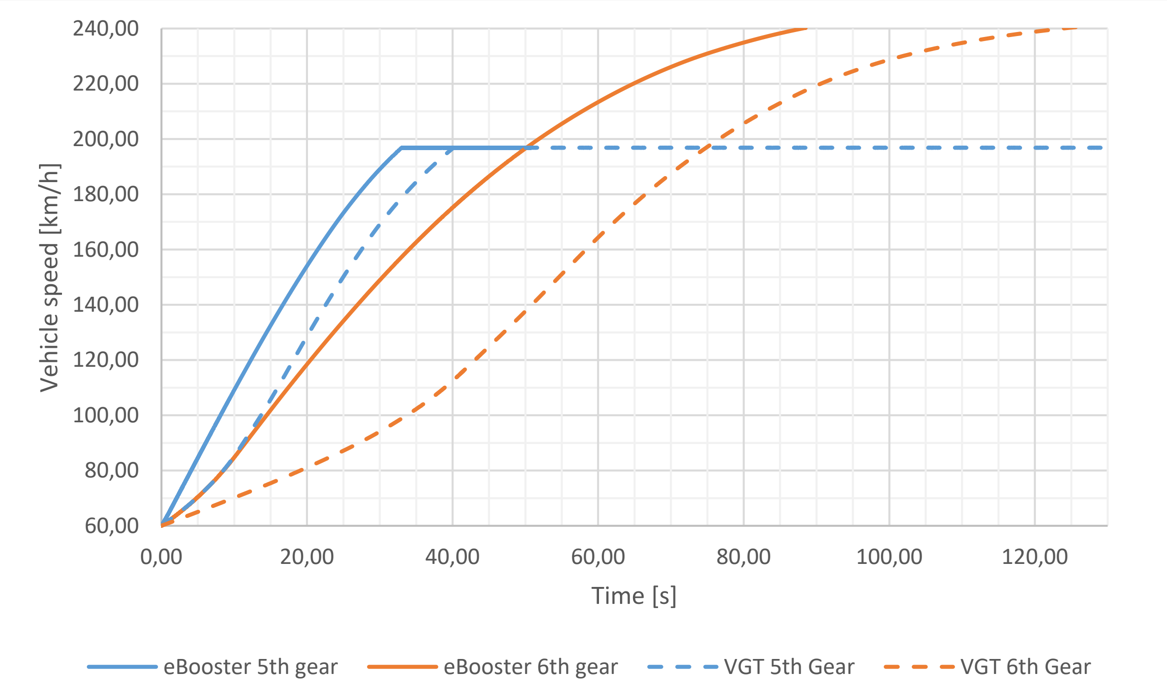


Figure 42: Speed graph.

behavior of vehicle when driver exactly knows how big a power reserve at the moment is and in general reminds behavior of naturally aspirated engine.

In that scenario eBooster at 5th and 6th gear was active for 10 and 30 seconds respectively, using 5% and 10% of battery capacity respectively till engine reaches approximately 2500 RPM when conventional turbocharger provides enough pressure. That also provides understanding that battery with approximate capacity of 13 Ah is sufficient for that kind of vehicle, considering possibilities of combination with other hybridization components and use of energy recuperation systems.

Table 5: Acceleration times from 60 km/h

		5th gear		6th ger		
		eBooster	VGT	eBooster	VGT	
Time to speed	80,0 km/h	4,07	8,49	8,53	19,07	[s]
Distance to Speed	80,0 km/h	78,99	163,05	163,72	369,60	[m]
Time to speed	100,0 km/h	8,11	13,68	14,46	33,71	[s]
Distance to Speed	100,0 km/h	180,11	292,11	311,78	732,79	[m]
Time to speed	120,0 km/h	12,28	18,14	20,49	43,07	[s]
Distance to Speed	120,0 km/h	307,46	428,17	496,19	1016,97	[m]
Time to speed	200,0 km/h	-	-	51,86	76,61	[s]
Distance to Speed	200,0 km/h	-	-	1922,85	2530,18	[m]

5.4.3. Driving cycle simulation

At last, homologation WLTC driving cycle was simulated. Shifting strategy was adapted to reach best fuel economy (Figure 43). However, results of simulation showed that WLTC cycle has too low demands on engine load. Due to relatively high displacement engine works in almost NA regime and so benefits of eBoosting are not so obvious in that case, since it's not actuated for most of time. Average BMEP was only about 3 bar. Nevertheless, due to more efficient engine mapping, with lower BSFC in low engine speeds, average consumption lowered to 6.7 l/100 km for about 4% comparing to conventional VGT version (7 l/100 km) and even 20% (8,5 l/100km) comparing to real production car consumption [20]. However, comparing results of that simulation with real production car is not accurate, since values of consumption are based on NEDC cycle whereas WLTC cycle was simulated. Shifting strategy also varies with homologated one, nevertheless that simulation was made to be as close to reality as possible, so comparison with values provided by automotive community on relevant web sites, such is for example www.spritmonitor.de, is on place.

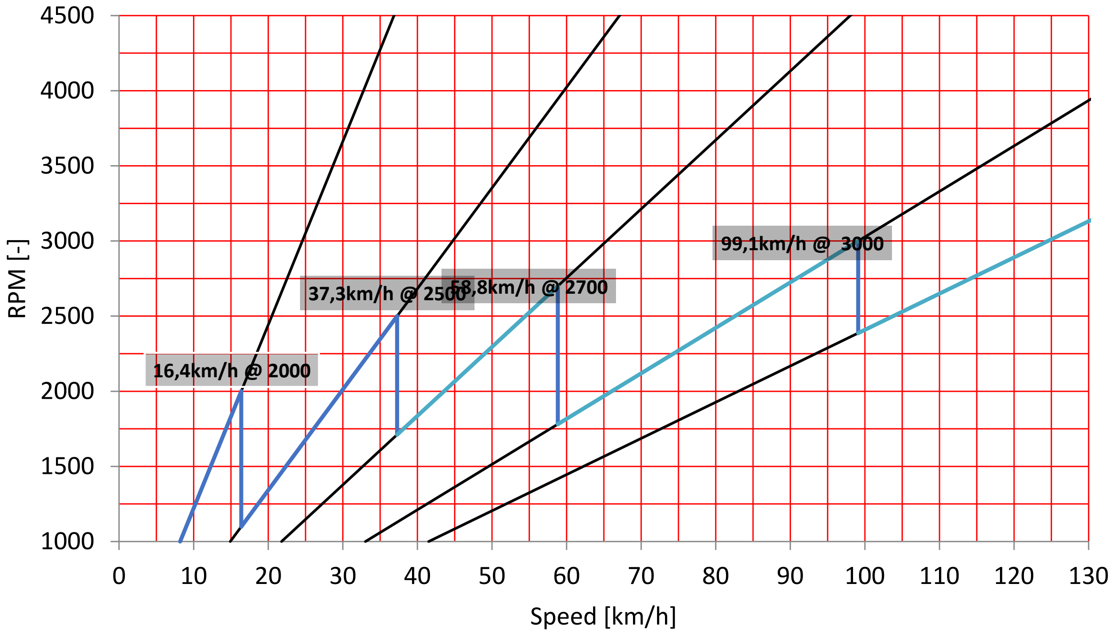


Figure 43: Shifting diagram

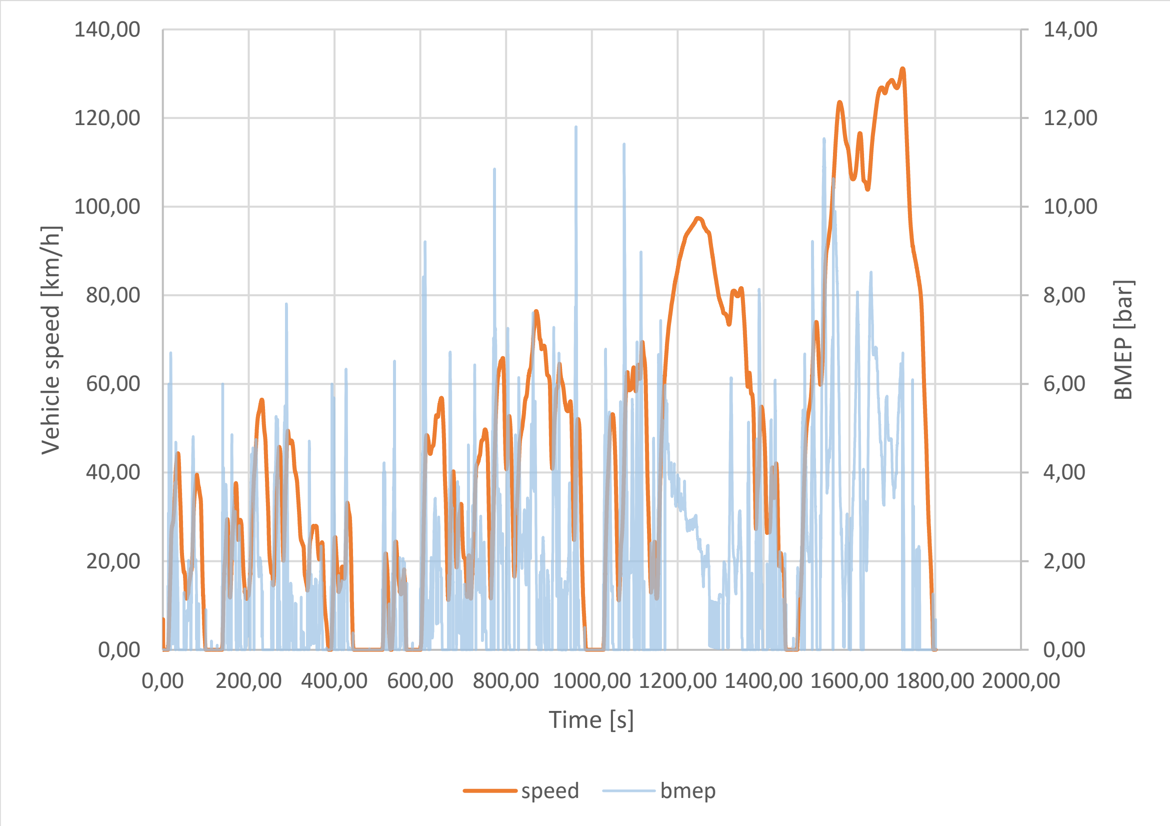


Figure 44: Engine BMEP and vehicle speed during test cycle

5.5. Limitations of model

Although demand on model was so it reflects reality as close as possible, some values were assumed approximately, since it wasn't possible to acquire those values in senseful time, though those approximations are not crucial for results. The eBooster map was generated with GT-Suit tools [21] based on target design point and isn't ideal. Some factors were not considered in these simulations, like EGR and aftertreatment systems. Nevertheless, in case of most of those assumptions a sensitivity analysis was made to prevent anyhow substantial impact on the results.

Operational area of generated performance map, as was shown in figure 27 is quite narrow, however in combination with existing turbocharger, eBooster is supposed to have relatively wide operational area up to 2500 RPM. In the same time, it has to provide compression of almost 3:1 in lower engine speeds which complicates scaling process and forces to keep to set it the way it is, with low efficiency at higher RPM, since surge margin is much more essential problem. Nevertheless, those imperfections are only leading to slightly higher demand on electrical harness and it might be optimized in future.

6. Conclusions

The task of this thesis was to build a 1D simulation model of a turbocharged engine with electrically assisted supercharger and investigate potential advantages of that concept. Due to the fact, that this concept is not commonly used in industry yet a lot of assumptions have been made to find out the path to working concept.

First of all, research has been made, to find out what is actual situation with e-Boosting, what solutions already exist and what tendencies and main direction are topical for now. The research showed, that only a few production cars are equipped with e-assisted superchargers and in e-assisted turbocharges are used in motorsport. However, it resulted in at least a basic idea of senseful concept of eBooster.

Then I created a 1D simulation model of existing turbocharged engine, for which I was able to find almost all the necessary information, to make a model, that is as close to reality as possible. That model was optimized and results were compared to measurements of actual engine to achieve compliance with reality and trust in simulated results.

After model was optimized, developing of eBoosting concept began. During the work on that thesis different concepts and ideas were simulated, though many of them showed up to be a dead-end and whole process had to be started almost from the beginning which required hundreds of hours of computational time. In the end a model with serial eBooster was developed with possibility of producing a real-life prototype incl. whole controlling logic.

Later I prosed to simulations. During steady-state simulations concept got optimized to achieve best performance and efficiency considering real life limitations, such is temperature and pressure in combustion chamber, fuel pump characteristics, drivability, electrical harness parameters etc. Based on those simulations were designed eBooster performance map and modifications for existing turbocharger. As a result, full speed characteristic of engine and many other findings came out.

Main goal of the thesis was to simulate engine in transient operation to evaluate potential advantages of this concept. Acceleration simulations showed significant improvement of vehicle dynamics in case of high load demand. Performance became even better than some modern engines, even though performance of simulated engine is limited by the obsolete fuel system and purely matched conventional turbocharger. However, WLTC cycle wasn't sufficient to prove benefits of eBoosting during driving cycle, due to low load demand. Results achieved I simulations let me assume, that RDE cycles might be more relevant in study of eBoosting, however due to high demand on computational performance and subsequently time it wasn't possible to prepare and run those simulations. Simulations also showed, that eBoosting has a great potential for maximizing power output for example for motorsport-oriented applications. Still, designed system shows to have a potential. Electrical power system of 11 kW and 13 Ah battery seems to be sufficient for any drive style and on-the-road situation.

Another positive result of that work, is that from the very beginning GT-Suite model was developed with an idea of modular system, which means, that with minimum work it's possible to modify that model to simulate any other engine for eBoosting potential evaluation. That makes that model a handy tool for future research and development providing a whole methodic for eBoosting evaluation.

Due to significant complexity of the theme of this thesis it wasn't possible to simulate every possible scenario and so there is still plenty of simulations that could've been done and parties of model that should be optimized better. For now, main problem is the eBooster efficiency map. Although a lot of time was spent on its optimization, it's still generated with GT-Suite's algorithms and doesn't cover whole operation area which leads to low efficiency and higher demand on electrical system. Nevertheless, those troubles leave wide space for future research yet the whole model. offers a good basis for it.

In the end, e-assisted supercharging seems to be an interesting technology with a potential to become more common in production car. Not only it helps with car drivability in case of heavily downsized engines, which is essential considering upcoming Euro 7 emission regulations, but is also promising for performance targeted vehicles and motorsport applications which was proven by simulations in this thesis.

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