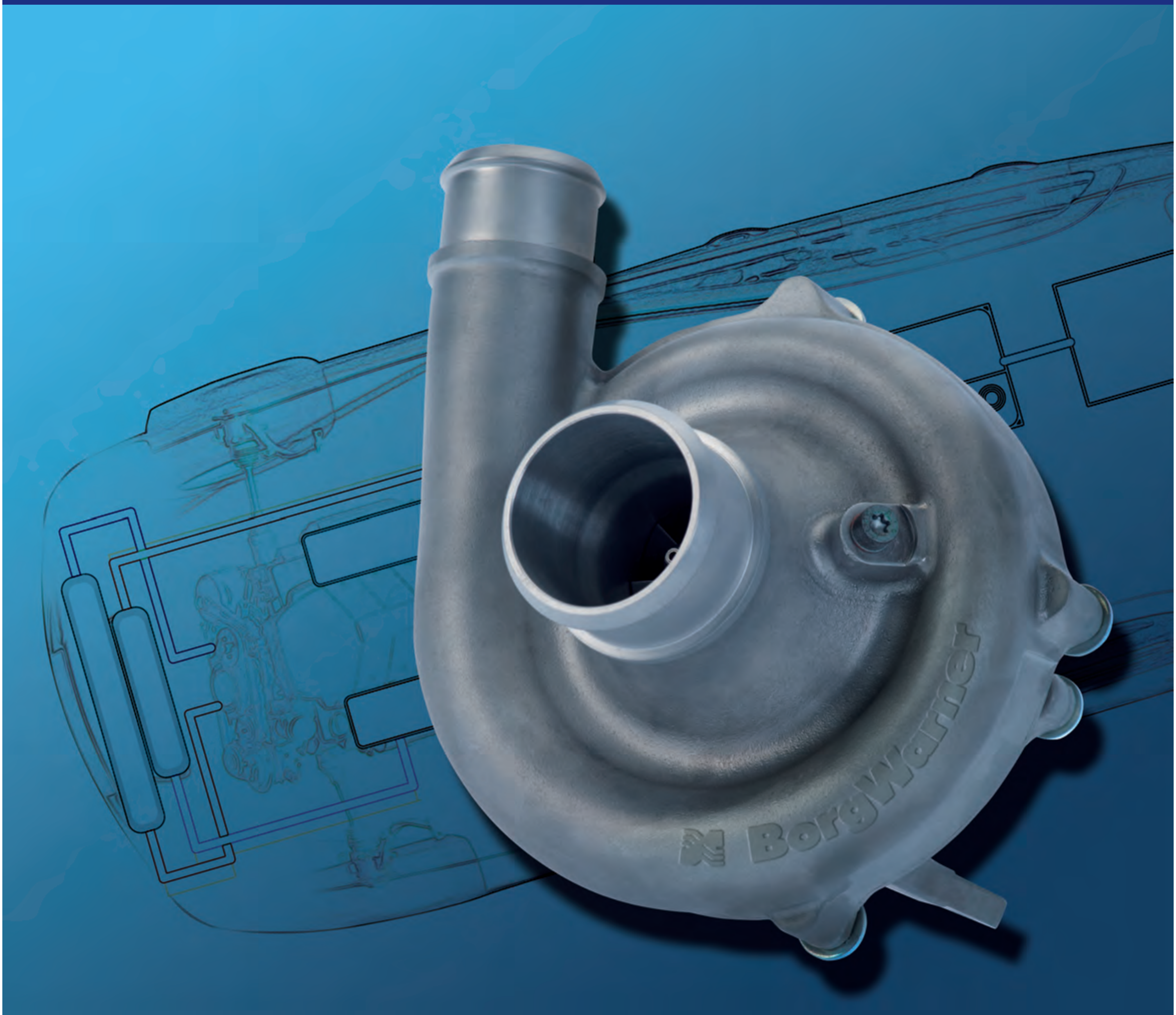
Application and Design of the eBooster®
from BorgWarner



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Application and Design of the eBooster® from BorgWarner

With an electrically assisted compressor, the eBooster®, BorgWarner supplements conventional turbocharging concepts improving boost pressure and transient engine behaviour for low engine speeds. This will both provide engine power increase, as well as a fuel consumption advantage due to the lower back pressure at high load and less need for fuel enrichment at full load.

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Electrically assisted Boosting becomes attractive

Since the 1960's, serial production turbochargers for automotive applications were developed, first for gasoline engines, later very successfully for diesel engines. Significant increase in torque and power were key enablers for engine downsizing and down-speeding. With that, turbo response became an increasing challenge. Besides continuous improvement of turbochargers, several new concepts were evaluated, like combining turbocharger and mechanical compressor, using multiple turbochargers in parallel or serial configuration or using electrically assisted turbochargers [1].

Electrically assisted boosting systems have repeatedly been investigated, starting in the 1990's. At 12 V, with state-of-the-art power electronics and microprocessors at the time, boost assist power around 2 kW was realised [2]. With the inertia of turbine, compressor and available electro motor technology, drive power of electrically assisted turbocharges in transient operation was almost used up to accelerate the rotating assembly, before significant boost pressure was generated. At the same time, the available electrical power and energy from the vehicle system was significantly lower than it is today.

With increasing vehicle electrification, significant progress in power electronic parts, compact electric motors and microprocessors for motor control, power levels of 2.5 kW at 12 V and 5 kW at 48 V seem feasible, and electrically assisted boosting becomes attractive again. Especially electrically driven compressors look promising because without turbine, rotor inertia can be kept low [3].

Benefits of an electrically driven Compressor for a Combustion Engine

BorgWarner developed an electrically assisted compressor, the eBooster®, to improve boost pressure and transient engine behaviour for low engine speeds without impact on the engine gas exchange, since without additional turbine, there is no backpressure increase. This is a significant advantage, especially with gas engines susceptible to engine knock. The independence of the eBooster from exhaust gas allows more flexible packaging, leaves, as compared to multistage turbochargers, more exhaust heat for the after treatment system, and causes less heat flux into the engine compartment.

The preferred position for the eBooster is downstream from the turbo compressor. Due to the lower boost pressure ratio, the power consumption is lower as well as the required compressor map width. Thus, electrical boosting can be extended over a larger engine speed range. Positioning upstream of the turbo compressor would effectively lower the usable turbo compressor map width, since the higher air density would shift the compressor operating point towards the surge limit.

The eBooster can improve transient behaviour, maintaining engine output with conventional turbo matching. Alternatively, transient response can be kept constant, and a larger turbine with lower back pressure can be used. This will both provide engine power increase, as well as a fuel consumption advantage due to the lower back pressure at high load and less need for fuel enrichment at full load.

		2.0-l	1.6-l
Rated power (at 4000 rpm)	[kW]	128	
Specific power (at 4000 rpm)	[kW/l]	64	80
Rated power (at 1750 rpm)	[Nm]	360	
Specific torque (at 1750 rpm)	[Nm/l]	180	225
Max. brake mean effective pressure	[bar]	23	28

Table 1. Comparison of engine concepts

The following analysis shows the potential of a 12-V eBooster with 2 kW power on a diesel engine, with focus on emission cycle operating range [3]. Basis is a 2.0-l engine with single stage variable turbine geometry turbo (VTG). Compared are two equal power 1.6-l engines, one with VTG turbo combined with eBooster and one with a regulated two stage system (R2S®), as shown in Table 1.

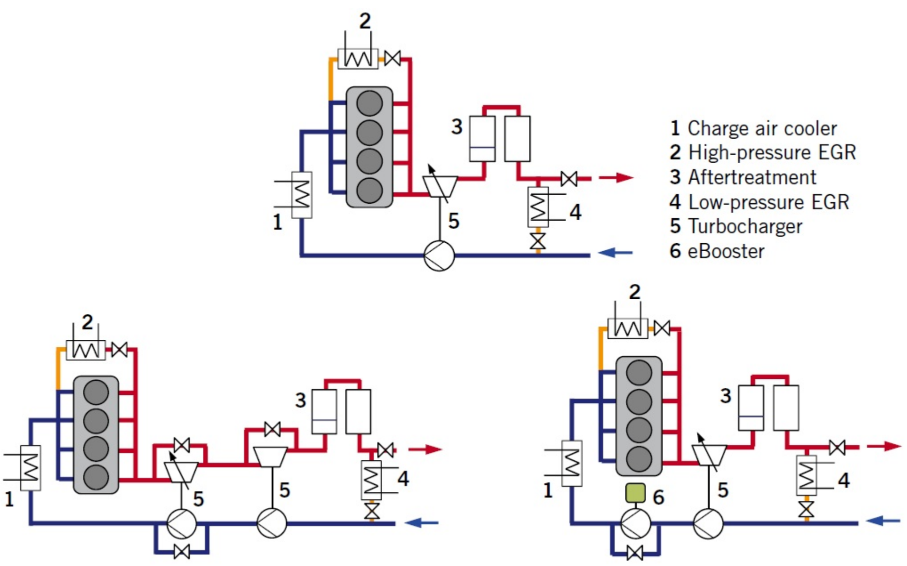

Figure 1. Concept of 2.0-l base engine (top) and 1.6-l engine with R2S (left) andVTG + eBooster (right)

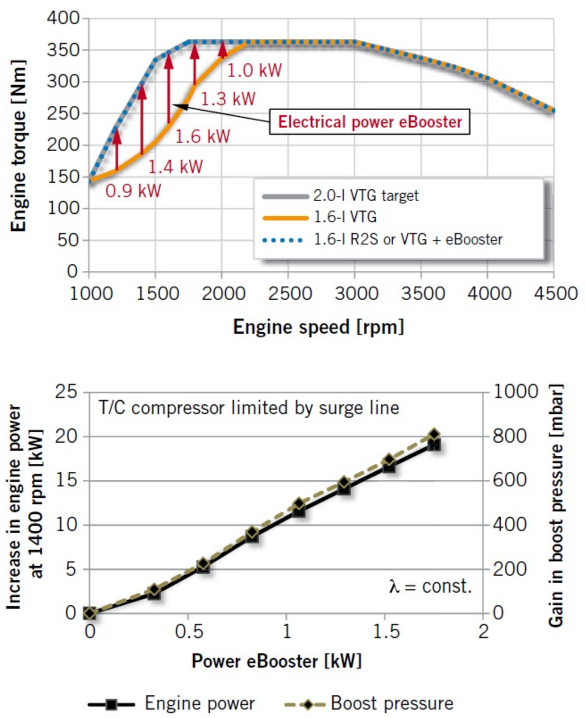

Figure 2. Torque curves for 2.0-l engine versus 1.6-l single-VTG and two stage concepts (top) and additional engine power achieved through electrical boosting at 1400 rpm (bottom)

The turbocharger matching has been optimised for every case, as it is shown in Figure 1. The eBooster (6) with bypass valve is positioned behind VTG compressor (5), but before charge air cooler (1). The high pressure stage of the R2S turbo is a VTG turbine (5).

The 1.6-l engine with VTG without eBooster operation shows a significant gap in torque, Figure 2 (top), since the turbocharger was adapted for higher boost pressure at full load to achieve power targets. Thus, in part load, the surge margin is limiting torque earlier. The eBooster allows compensating the torque gap, the electrical power required in the respective speed points is indicated in Figure 2 (top).

Figure 2 (bottom) shows the increase in engine power at 1400 rpm versus the electrical power of the eBooster. An amplification factor of around seven to ten can be achieved through the increased amount of air for the combustion process. With increased air mass flow, turbine power will go up, thus, the VTG vanes can be opened further, the turbine efficiency will go up, and the air exchange losses will decrease, so overall, a better fuel efficiency will be achieved.

The R2S system also meets torque targets. However, the high pressure stage does take around a factor two more energy from the exhaust gas flow as the eBooster is consuming electrically, as Figure 3 (top) shows. In case the electrical energy is coming from recuperation, the overall energy balance is advantageous for the eBooster, otherwise for the R2S system.

The transient response of the concepts was evaluated for load steps at 1500 rpm, see Figure 3 (bottom). The VTG remains mostly

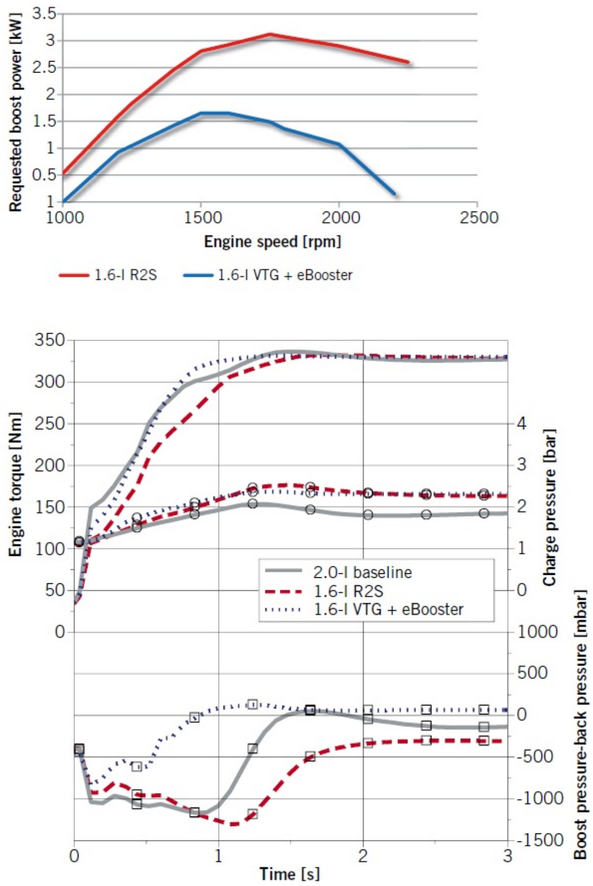

Figure 3. R2S turbine power and eBooster electrical power versus engine speed (top) and load step at 1500 rpm from start torque at 25 Nm (bottom)

closed, only at 5 % dynamic reserve to surge line, it is slightly opened. The eBooster speed is controlled to achieve boost pressure target.

The torque curves show the initial advantage of the 2.0-l engine before boost pressure builds up. With boost pressure from the eBooster, the 1.6-l VTG engine torque gradient becomes steeper; the full load torque is achieved earlier than with the 2.0-l engine and even the R2S engine. However, the R2S system can maintain high boost pressure also in steady-state operation, where the eBooster can only deliver transient boost.

Figure 4 (top) shows an FTP-75 drive cycle with the power consumption of the eBooster, calculated with a dynamic drive model for a premium car with power to weight ratio of 13 kg/kW and a six-speed transmission. The eBooster is operated with 2 kW and a minimum speed maintained of 6000 rpm. In the cycle, the average power consumption is around 210 W. The eBooster is in idle around half of the time. Switching it off would save around 13 W. With additional boost pressure from the eBooster, a higher amount of low pressure EGR can be used and gas exchange advantages can be generated. With that, around 4 % fuel efficiency increase is expected, with only slight disadvantages in NO_x emissions compared to the R2S concept. Advantages in particulate emissions are expected compared to the reference engine, since the time of the air/fuel ratio at the smoke limit decreased by 5 %.

Requirements of the electrically driven Compressor

From the eBooster function, clear design re-

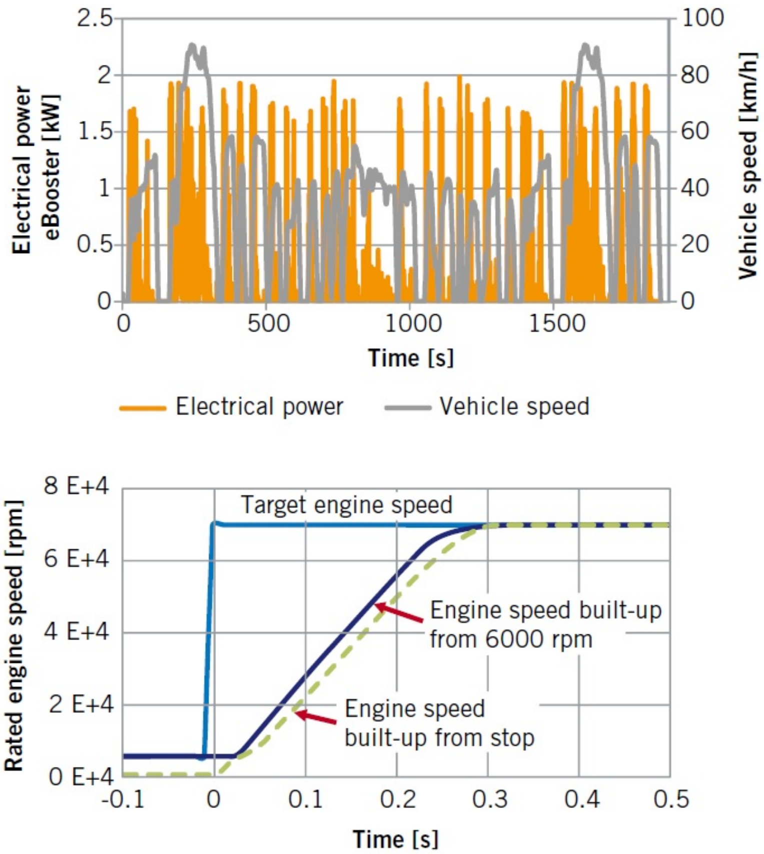

Figure 4. FTP-75 with eBooster electrical power consumption (top) and eBooster transient acceleration from idle and standstill (bottom)

quirements could be derived:
- the inertia of the electrical motor has to be minimised
- electrical and mechanical losses need to be minimised
- the motor has to be robust against high temperatures
- a very compact design with integrated power electronics
- very efficient power electronics (at 5 kW electrical power, every percent efficiency loss means 50 W of heat flux to be conducted away from the power board)
- eBooster variants have to be modular for 12- and 48-V variants
- NVH has to be considered in the concept.

Design of the electrically driven Compressor

The design concept decisions were guided by the above key requirements. A brushless permanent magnet DC motor was selected, because it is clearly more efficient than asynchronous or switched reluctance motors. The motor has to be very robust to high temperatures to endure high on time, thus, samarium-cobalt magnets, being magnetically stable beyond 300 °C, were selected.

Also, the permanent magnet motor does not need magnetisation energy from the power electronics, which helps keeping it efficient and compact. The motor was designed such, that motor torque over motor rotation does only show low torque ripple, to minimise high frequency noise from the motor.

Figure 4 (bottom) shows the motor transient response to a full speed command, both starting from 6000 rpm idle speed and from a motor hold position. From idle, 90 % of maximum speed is reached after 230 ms, from motor hold in 250 ms. Electronic circuits and bearings are designed such, that the eBooster can either be run in idle continuously, or can be put in standstill.

When choosing the eBooster operating speed, it had to be considered, that the energy to accelerate a rotor is proportional to the speed squared. Thus, an optimum had to be selected between a large motor with low speed, a large compressor wheel but a very quick speed ramp and a small, very high speed motor with small compressor and longer speed ramp.

Specification	12-V eBooster	48-V eBooster
Max. current [A]	200	130
Built-up to 90 % rated engine speed [ms]	250	230
Max. power output [kW]	2.4 (transient) 1.7 (nominal)	6.2 (transient) 5 (nominal)
Rated engine speed [rpm]	60,000	70,000
Pressure ratio [-]	1.3	1.45
Air flow [kg/h]	150	300
Switch-on time over lifetime	Appr. 50 % at rated power	Appr. 33 % at rated power
Max. time boost-event [s]	12	14
Max. on-time	60 to 80 %	60 to 80 %

Table 2. Key eBooster product specifications

A compromise was chosen at a speed of 70,000 rpm, to achieve an overall homogeneous package with roughly similar diameter between motor, power electronic and compressor side of the eBooster. The 48-V eBooster has an overall length of only 170 mm (including the compressor inlet flange) and a diameter of only 135 mm.

Also, the stator was optimised for long on-times and high duty cycle by using a high density copper filling and designing for a good heat transfer to the housing. For low heat generation, the power electronics is using parts with lowest resistance specifications and highly efficient capacitors, the CAN interface is integrated. A good connection from electronic board to housing guarantees an efficient heat transfer.

Both air and water cooling were investigated. Air cooling would be preferred from a vehicle integration standpoint. However, air cooling is only feasible for the 12-V eBooster. With the 48-V eBooster, only water cooling with good heat transfer to stator and power electronic board was feasible.

Finally, with all these design concepts, excellent specifications could be achieved for the eBooster. Table 2 shows typical values, especially on-time and duty cycle are however application specific and depend on water, air and eBooster ambient temperatures in the respective vehicle application. To achieve best duty cycle values, usage of water from the low temperature circuit is recommended, however not mandatory. With favourable operation conditions, the 48-V eBooster can achieve around 2 kW permanent power.

To ensure that the eBooster is always available for boosting in the vehicle application, BorgWarner developed a simulation tool to predict temperature and eBooster availability. That can be used as basis for load management. Lower currents, and higher power for larger displacement engines and more benefits in transient performance and fuel economy are advantages of the 48-V eBooster. A simulation, using customer drive profiles and load cycles, can determine eBooster energy consumption, such that the OEM can early on check his vehicle electric system.

Summary

BorgWarner’s eBooster supplements the conventional turbocharger. Even at low engine speeds, boost pressure can be supplied very quickly to enhance engine transient response. With that, the eBooster offers potential to increase engine power. With respective matching of the overall system eBooster and turbocharger, both fuel efficiency improvements and, especially with diesel engines, optimisation of pollutant emissions are feasible.

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