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Optimization of the Performance of a Formula SAE Engine by means of a Wastegate Valve Electronically Actuated

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Abstract

The engine and vehicle design in Formula SAE competition has to accomplish a strict regulation. In order to limit the maximum power, an air restrictor of 20 mm of diameter is imposed in the intake line. To overcome the limitations caused by the restrictor, Firenze Race Team equipped its one-cylinder engine with a turbocharger, which is conventionally provided with a wastegate (WG) valve to limit the maximum boost pressure and avoid knocking phenomena. Typically, the WG valve is controlled by a pneumatic actuator, which opens the valve according to a defined and constant maximum boost pressure downstream the compressor in the whole engine operating range. Therefore, the boost pressure at high engine speed, in which knocking problems are less intense and the volumetric efficiency is lower, is limited by the threshold value defined at medium-low engine speeds, i.e. the pneumatic WG limits the maximum power that the engine can supply. In this study, the implementation of an electronic control system for the WG valve is described together with a dedicated control strategy aimed at providing the desired boost pressure at full load for each engine speed, in order to get the maximum power avoiding knocking phenomena. The electronic WG provided higher power values and a more extended torque curve in comparison to the conventional pneumatic one.

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Keywords: Formula SAE; SI engine; Turbocharger; Wastegate; Control; Test bench

1. Introduction

In order to limit the maximum power of internal combustion engines, the rules of Formula SAE impose the use of an air restrictor on the intake duct. The restrictor for gasoline engines has a diameter of 20 mm. With the aim of

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compensating the power loss, the FSAE teams usually either introduce a plenum along the intake line after the throttle body or install a turbocharger between the air restrictor and the throttle body [1].

Nomenclature

CR	Compression Ratio	PP 2Dmap	Boost pressure/WG valve position map
ECU	Electronic Control Unit	PWM	Pulse-Width Modulation
FRT	Firenze Race Team	SI	Spark Ignition
FSO	Full Scale Output	SLP 3Dmap	Engine speed/Load/Boost pressure map
IC	Intercooler	TC	Turbo Compressor
IMEP	Indicate Mean Effective Pressure	WGe	Electronic Wastegate
PID	Proportional Integrative Derivative	WGm	Mechanical Wastegate

Since the 2014 season, Firenze Race Team (FRT) decided to adopt a single cylinder, SI, 4 stroke engine for enduro application. By doing so, a lightweight and agile vehicle was obtained, characterized by a good weight-to-power ratio. In order to support the engine design and to quickly perform its optimization analyses, a 1D numerical model of the engine was first calibrated. Upon examination of the comparison between numerical and experimental results in terms of torque of the naturally aspired baseline engine (Fig. 1 (a)), the reliability of the numerical model is apparent. The simulation of the original engine provided with the restrictor was then carried out; Fig. 1 (b) shows the simulated performance drop, which was deemed to be inacceptable for a race car [2-5].

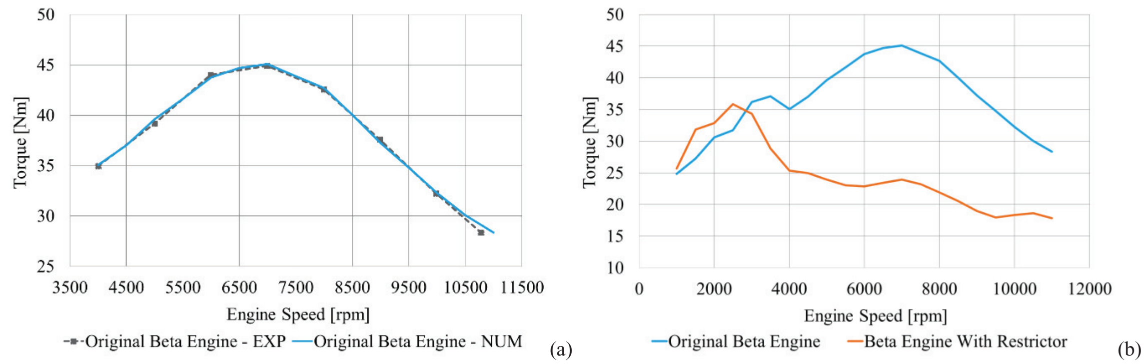


Fig. 1. (a) Torque at full load condition of the original engine: comparison between experimental data and the numerical ones.
(b) Comparison of the performance of the Beta 520rr engine in full throttle condition with and without air restrictor (numerical results).

In a previous study [6], an innovative plenum provided with a variable geometry intake system was investigated by means of the calibrated numerical model. The plenum sizing was a compromise between maximum performance, prompt engine response and vehicle layout. Is worth noticing indeed that, in general, the bigger is the plenum, the higher is the maximum power, but the engine response during transient operation is downgraded. The final proposed solution was characterized by a 4L plenum, which guaranteed a good level of maximum power, combined with a variable length intake duct, which excluded the plenum at medium-low loads ensuring a good engine response. A second evaluated solution was based on the use of the turbocharger (TC) MGT12 provided by Honeywell-Garret [7]. From a numerical comparison between the turbocharged engine and the engine with the innovative plenum, the advantage in terms of maximum performance offered by the first solution was evident.

The MGT12 TC is conventionally equipped with a pneumatic actuator for the control of the wastegate (WG) valve. This solution is mechanically simple, reliable but limits the maximum IMEP that the engine can supply at each engine speed. More in detail, since the maximum boost pressure is limited by the onset of knocking phenomena, the pneumatic WG is calibrated as to avoid this issue in the worst engine operating points, i.e. at full load in the medium-low engine speeds. The boost pressure at the higher engine speeds is then intrinsically limited, with a consequent reduction of the achievable maximum power. To overcome this drawback, the pneumatic WG was replaced with a WG electronically actuated. The electronic WG was controlled in closed loop with a real-time feedback on the boost pressure. The electronic actuator allows the control logic to regulate the WG opening step-by-step and to optimize the overpressure for each engine operating condition, particularly at full load, with a consequent increase of torque and power. In the relevant technical literature, some studies analyze the wastegate valve management in order to improve the engine functioning. For example, the Yang et al. [8] analyzed the optimization of the wastegate control at medium engine speeds for a diesel engine. Wakeman et al. [9] instead focused the attention on a closed-loop turbocharger control aimed at achieving the engine maximum performance and a better transient response. From the technical survey, it was apparent, however, that the adoption of a turbocharger provided with an electronic WG is an innovative solution in Formula SAE competition, with interesting prospects in terms of optimization of both the maximum performance and the drivability of the vehicle.

2. Experimental setup

The engine adopted by FRT during 2015 and 2016 seasons is a single cylinder, 4 stroke SI engine supplied by Betamotor. Since the rules impose an air restrictor of 20 mm on the intake duct, the engine was properly modified in order to re-gain an acceptable level of performance. The engine layout is depicted in Fig. 2. The main modifications made on the original engine are:

- Installation of the TC following FSAE rules.
- Installation of the air-to-air intercooler after the compressor to reduce the intake air temperature.
- Replacement of the original carburettor with two injectors. The first injector, positioned 5 cm upstream the intake valves, is used at low medium loads and speeds in order to avoid gasoline condensation along the intake duct, while the second one, installed on the throttle body upstream the IC, is used at high speeds and loads to guarantee a good air-fuel mixing.
- Reduction of the compression ratio from the original value of 12.5 to 9.04, ensuring high values of boost pressure avoiding, however, knocking phenomena.
- Reduction of the valves' overlap to 0°, penalizing the scavenging of exhaust gases, but increasing the trapping efficiency. This solution was due to the fact that the original valve timing was characterized by an overlap between intake and exhaust valves of about 60 degrees; in case of a turbocharged engine, this feature caused however a super-scavenging effect and consequently a considerable fuel short-circuit, since the engine is provided with a PFI system.
- Introduction of a Hall-effect sensor placed on the cam cover, in order to phase injection and ignition with the intake cam passage. The presence of an intercooler of 1L between the engine and the throttle body, in fact reduces the amplitude of the pulsating flow; the pressure signal at the throttle body is then reduced and the phasing of both the injection and the ignition with a pressure sensor becomes fairly feasible.

The main features of the FRT car engine are finally summarized in Table 1. In particular, during the development of the engine for the 2016 FRT car, special attention was paid to the realization of an electronically actuated wastegate (WG) valve, in order to ensure a fine regulation of the charge pressure at each engine operating point.

Turbochargers are indeed conventionally equipped with a pneumatically actuated WG valve. This solution is simple, reliable and cheap, but does not allow a fine regulation of the valve opening and the boost pressure, especially for a single-cylinder engine, which is characterized by a strongly pulsating airflow.

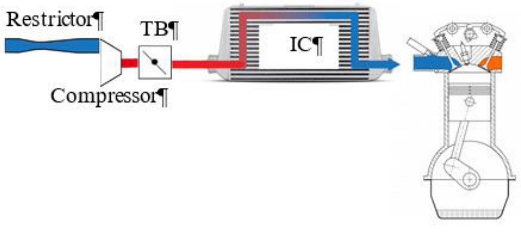


Fig. 2. Turbocharged engine layout according to the Formula SAE rules.

Table 1. Betamotor 520RR turbo engine characteristics.

Type	Single Cylinder, 4-Stroke, Spark-Ignition, Liquid Cooled
Fuel / Fuel System	Gasoline / PFI, double injectors
Displacement / Stroke X Bore / CR	518 cc / 63.4 mm X 102 mm / 9.04:1
Air Charging System	Honeywell MGT 12 Turbocharger with WG electronically actuated
Air cooling	Air to Air intercooler

A possible way to more accurately control the charge pressure is represented by the adoption of an electronically actuated WG valve. The electronic actuator in fact allows high actuation speeds and very precise boost pressure regulation. In particular, a Honeywell electronic wastegate was adopted in the present application. Wastegate valves electrically actuated (WGe) are also provided with a linear electric motor and a potentiometer for the measurement of the beam translation; the two devices communicate by means of a can bus protocol with the ECU of the engine. The control logic for the actuation of the WGe of FTR engine is based on the continuous measurement of the pressure after the compressor. The charge pressure is then managed in closed loop with a PID control [10].

In the engine ECU (Mectronik MKE6), the WGe management is based on a 3D map, engine speed – load – boost pressure (*SLP 3Dmap*). For each load – engine speed point, a specific boost pressure value is defined (Fig. 3 (a)). The boost information is then converted into a specific actuator position (PWM signal); the correlation between the boost pressure and the WG valve position is defined with another specific map into the engine ECU (*PP 2Dmap*) [11]. The power control of the WGe is entrusted to an Arduino shield combined with a H bridge.

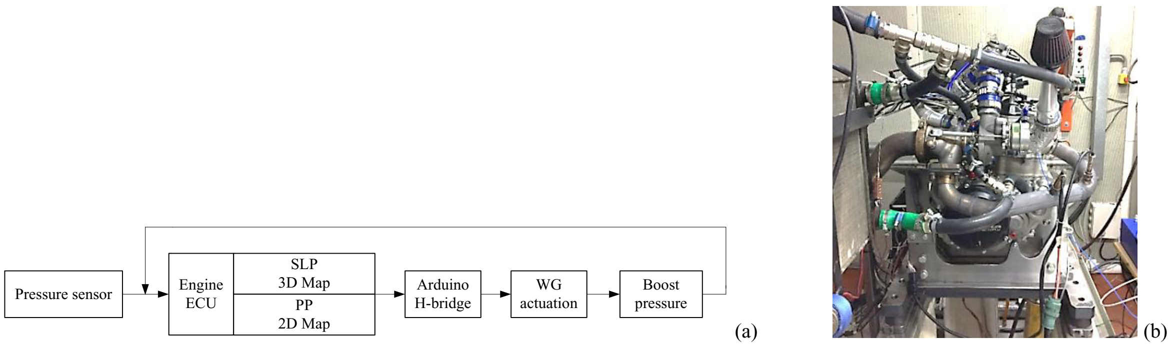


Fig. 3. (a) Control logic for the actuation of the WGe; (b) Beta 520 engine at the test bench.

During the engine operation, the boost pressure is constantly monitored and the control logic actuates the WG in order to match the target pressure. During the calibration of the engine at the test bench, the SLP 3Dmap and the PP 2Dmap were defined with the aim of achieving the maximum power without knocking phenomena.

All the experimental tests were carried out at the engine static test bench of the Department of Industrial Engineering of the University of Florence (DIEF). The Eddy Current Dynamometer is the APICOM FR 150 (Power 110 kW, Max Torque 450 Nm at 2375 rpm, Max Speed 13000 rpm). The FRT engine at the test bench in shown in Fig. 3 (b). A high-frequency piezoelectric sensor was used to measure the pressure inside the cylinder (AVL GR14D, max pressure:150 bar).

The measurement of the working cycle was of course pivotal to find the best ignition advance and to fix the maximum charging pressure of the compressor at each engine operating point without occurring in knock phenomena. To properly trace off the PV diagram, the in-cylinder pressure was associated to the crank shaft position by using the AVL 365X optical digital encoder (max resolution: 720 pulses per cycle).

The static pressure upstream and downstream the compressor was monitored by using piezoresistive sensors. The charge pressure sensor was used also as feedback sensor for the control of the wastegate valve position.

Temperature sensors were located in several positions for a complete monitoring of the engine (intake temperature, temperature downstream the compressor, temperature after the intercooler). In addition, the temperature of the engine and turbine oil and the cooling liquid temperature were measured (K type thermocouples for the exhaust line; T type thermocouples for the intake line, the oil and the cooling liquid).

The engine was provided with a double O_2 sensor placed between the engine and the turbine on the exhaust duct, the first was used by the engine ECU (in order to control in closed loop the air to fuel ratio), while the second was acquired with the test bench instrumentation for the calibration of the fuel injection.

Finally, the fuel consumption represented one of the most important indexes of the overall engine efficiency. The fuel mass flow was measured with the AVL SORE PLU 110 volumetric fuel meter (max fuel flow: 45 kg/h; resolution: 0.2% FSO). In addition, a pressure sensor was installed inside the fuel line between the fuel flow meter and the injectors in order to monitor the correct functioning of the fuel pump.

3. Results

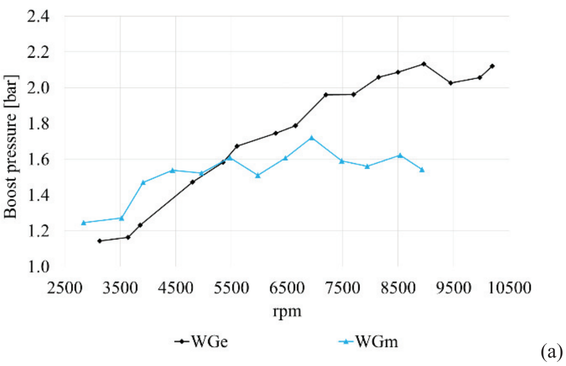
Differently from the pneumatic wastegate valve, which limits the boost pressure at the same maximum value in the whole engine operating range, the electronically actuated wastegate enables a variation of the maximum over boost in any operating point. As a consequence, in the first case the maximum performance of the engine at full load is limited by the most critical operating point in terms of knocking phenomena, while in the second case the electronic control system manages the wastegate valve in order to guarantee, for each engine speed at full load, the desired boost pressure.

During the experimental development, a boost pressure map was defined as a function of the engine speed and load, in order to get the maximum power at each engine operating point without incurring in knocking phenomena.

Fig. 4 (a) shows the maximum boost pressure at full load condition for the two typologies of wastegate valves. With the pneumatic wastegate, the maximum value of over boost is fixed at 1.6 bar for all the engine speed range; indeed, the overcoming of this over boost threshold at medium engine speed (5000-5500 rpm) could lead to the occurrence of the knocking phenomena. As discussed, this also implies a loss of potential over boost and power at higher engine speed.

Moreover, Fig. 4 (a) also highlights the operating instability of the pneumatic wastegate when working with a one-cylinder engine: the strong pressure oscillations in the exhaust manifold cause an irregular opening of the valve and then an oscillation of the charge pressure around the imposed maximum value.

On the other hand, the electronic actuator allows one to regulate the valve opening at each engine operating point and it is then able to provide the desired boost pressure for each engine speed. Furthermore, in order to obtain a smooth and linear engine response during acceleration, the electronic wastegate valve at low engine speeds can be maintained open more than the condition imposed by the pneumatic actuator.



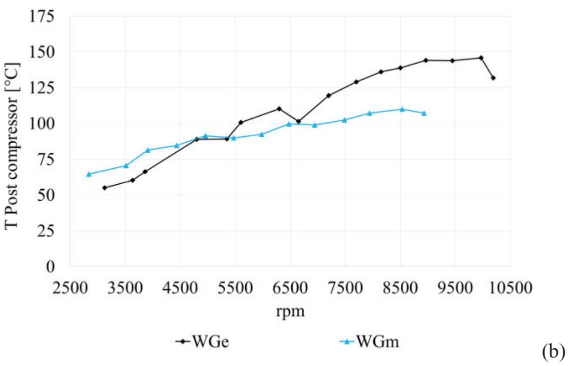


Fig. 4. (a) Boost pressure at the compressor outlet at full load. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm). (b) Air temperature at the compressor outlet at full load. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).

At higher engine speeds, i.e. starting from 5500 rpm, thanks to the possibility of regulating the over boost at each operating condition with the electronic wastegate, the mass flow rate is constantly increasing up to 8000 rpm, remaining then almost constant up to 10500 rpm (Fig. 5 (a)), despite the high increase of the air temperature at the compressor outlet (Fig. 4 (b)). Furthermore, as mentioned before, thanks to the direct control of the valve opening, the increase of the mass flow rate and engine power at low speeds is maintained linear for a soft and controlled acceleration. Conversely, in case of engine with the pneumatic wastegate, the mass flow rate reaches its maximum value at almost 7500 rpm, which is 22% less than that achieved with the electronic wastegate, and it falls down after 9000 rpm due to the insufficient overpressure (Fig. 5 (a)).

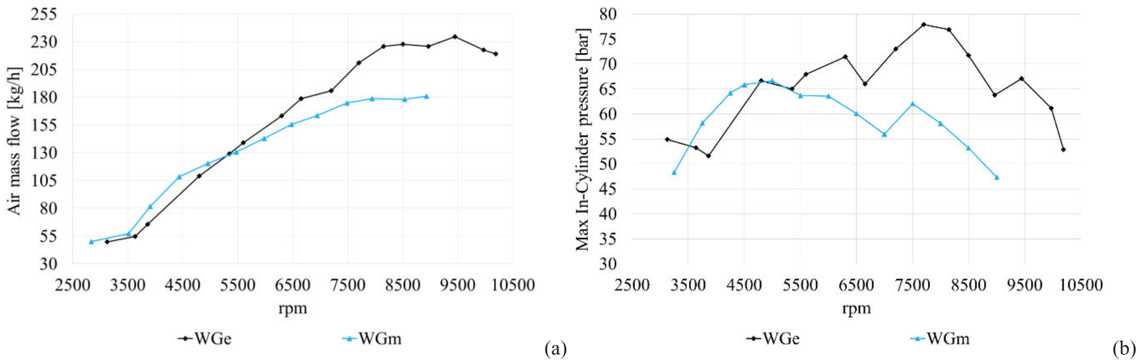


Fig. 5. (a) Air mass flow rate of the engine at full load. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).
(b) Maximum in-cylinder pressure at full load. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).

As shown in Fig. 5 (b), between 4500 rpm and 5500 rpm, both types of wastegate valves operate almost in the same way and the maximum pressure reached in the combustion chamber is the same too. At 5500 rpm, the PV cycle of the engine with both WG configurations is similar and the maximum torque is guaranteed without the occurring of knocking phenomena (Fig. 6 (a)). At higher engine speeds, the pneumatic actuator forces the valve to progressively open together with the speed in order to maintain the maximum overpressure at the value fixed at 5500 rpm (Fig. 4 (a)). As discussed, the performance at high speeds is consequently limited; conversely, the progressive control of the valve opening at each engine operating point made with the electronic actuator avoids possible knocking phenomena (Fig. 5 (b)). In these conditions, at high speeds (7500 rpm, Fig. 6 (b)), the PV cycle with the electronic actuator is much more swollen and the maximum in-cylinder pressure is higher even though constantly under the knock limit.

In Fig. 7 (a), the torque and power at full load obtained with the two wastegate typologies are finally shown. The turbocharged engines are compared also with the naturally aspired baseline version (original Betamotor engine).

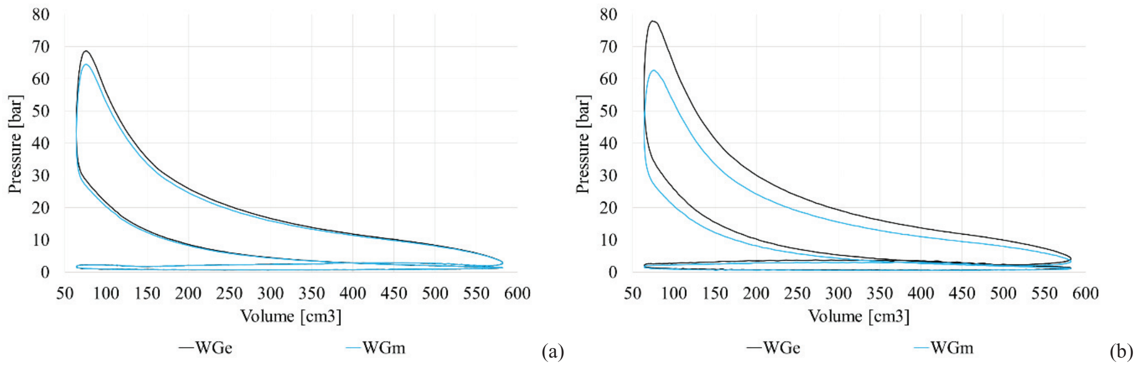


Fig. 6. (a) P-V cycle at full load and 5500 rpm. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).
(b) P-V cycle at full load and 7500 rpm. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).

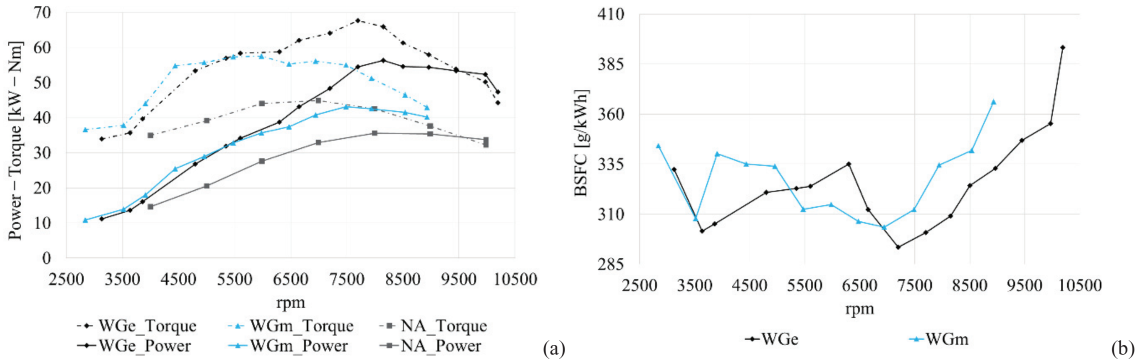


Fig. 7 (a). Torque and power at full load. Electronic WG valve (WGe) VS Mechanical WG valve (WGm) VS Naturally Aspired (NA). (b). Brake specific fuel consumption (BSFC) at full load. Electronic wastegate valve (WGe) VS Mechanical wastegate valve (WGm).

With the electronic actuator, a notably higher maximum power value was achieved (+ 23%), coupled with a linear increase at medium-low speeds and a greater extension. As shown in Fig. 7 (b), at full load, the electronic control of the wastegate valve allows to obtain an increase of the engine global efficiency, particularly at high engine speed. Thanks to the increase of the over boost, the turbulence and thermodynamic conditions around the top dead center promote a fast combustion and then an increase of the combustion efficiency. Furthermore, it is possible to presume that the increase of the flame velocity makes the combustion more isochoric, with an additional increase of the efficiency. At high engine speed, the electronic actuator keeps the wastegate close for a longer time with respect to the pneumatic one: despite the increase of the pumping cycle due to the increase of the exhaust back pressure, the pumping efficiency in enhanced thanks to the strong increment of the gross indicated cycle. The increment of the over boost does not influence the trapping efficiency of the Firenze Race Team engine due to the valve overlap that was intentionally designed very small. By referring to the Chen-Flynn friction correlation, due to the increase of the maximum in-cylinder pressure, at high engine speed the friction efficiency decreases.

In Fig. 8, the engine operating points at full load are reported on the compressor map.

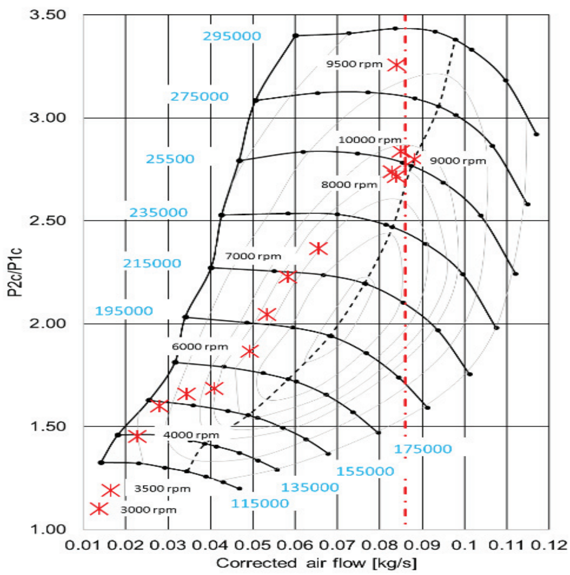


Fig. 8. Compressor map and operating points of the engine at full load with the electronic wastegate valve. Choke limit of the air restrictor.

The figure highlights two important aspects that will represent the main research areas for a further increase of the performance and the efficiency of the engine.

By improving the restrictor design, it could be possible to increase the flow coefficient and consequently the choke limit which is currently lower than the choke limit of the compressor. As a result, a further increase of the maximum engine power could be expected.

In addition, by taking also into account a new and optimized design of the restrictor, the engine could be equipped with a smaller compressor, since the choke limit of the current one is much higher than the maximum mass flow rate of the engine. A smaller compressor could work more centered in the maximum efficiency range, with a consequent reduction of the fuel consumption and, thanks to the lower inertia, it could also ensure a quicker response during transitory phases, with direct benefits in terms of vehicle acceleration.

4. Conclusions

Formula SAE rules impose an air restrictor of 20 mm of diameter in order to limit the maximum power of a 4S SI engine. A way to recover the lost power is to adopt a turbocharger. Usually, the maximum charge pressure is controlled by a wastegate valve pneumatically actuated. This typology of WG does not allow a fine regulation of the charge pressure in the whole engine operating range, and it penalizes the maximum engine power in order to avoid knock phenomena at medium-low speeds.

In the present study, the implementation of an electronically actuated wastegate on a single cylinder, 520cc, SI, 4 Stroke engine for FSAE application was presented. The use of a proper control logic based on the measurement of the charge pressure allowed to manage the WG valve position in order to maximize the engine performance at full load at each engine speed. The results showed the great benefits achievable by using the electronic WG with the specific control system respect to use a conventional mechanical WG.

References

[1] Mattarelli E, Rinaldini C. Development of a High Performance Engine for a Formula SAE Racer. SAE Technical Paper 2012: 01-0833, 2012.

[2] Bellissima A, Ferrara G, et al. Utilizzo di tecniche di sperimentazione con sensori dinamici di pressione per la taratura di modelli di calcolo 1D per motori a combustione interna. 63th ATI national congress, Palermo, 2008.

[3] Bellissima A, Carnevale E, A, et al. Messa a punto ed utilizzo di tecniche di sperimentazione per la taratura di modelli 1-d per la previsione delle prestazioni ai carichi parziali. 64th ATI national congress, L'Aquila, 2008.

[4] Walkingshaw J, McClintock S, McCullough G, McCartan C, et al. Experimental Validation of an FSAE Engine Model. SAE Technical Paper 2008: 32-0079, 2008.

[5] Cauchi J, Farrugia M, Balzan N. Engine Simulation of a Restricted FSAE Engine, Focusing on Restrictor Modelling. SAE Technical Paper 2006: 01-3651, 2006.

[6] Vichi G, Romani L, Ferrari L, Ferrara G. Development of an engine variable geometry intake system for a Formula SAE application. 69th ATI national congress, Milano, 2014.

[7] Mosetti J, GilorySmith B, Sick V. Design and Development of a Turbocharged E85 Engine for Formula SAE Racing. SAE Technical Paper 2008-01-1774, 2008.

[8] Yang, J. and Campbell, T., "Optimization of a Wastegate Turbocharged Medium Speed Diesel Engine," SAE Technical Paper 930195, 1993.

[9] Wakeman, R. and Wright, D., "Closed Loop Turbocharger Control with Transient Wastegate Functions," SAE Technical Paper 860487, 1986.

[10] Rydqvist J, Sandberg L, and Wallin R. A Turbocharged Engine with Microprocessor Controlled Boost Pressure. SAE Technical Paper 810060, 1981.

[11] Kharazmi S, Hajilouy-Benisi A and Mozafari, A. Experimental Investigation of Waste Gate Effects on Performance and NOx Emissions in a Turbocharged Aftercooled CNG SI Engine and its Turbocharger. SAE Technical Paper 2015-01-1957, 2015.