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Effects of *Pre-Lift* Intake Valve Strategies on the Performance of a DISI VVA Turbocharged Engine at Part and Full Load Operation

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Abstract

In the paper, the potentialities offered by an advanced valve lift design are numerically analyzed. In particular, the study is carried out by a 1D approach and regards the characterization of a VVA strategy named "*pre-lift*" applied to a downsized turbocharged four-cylinder engine. The *pre-lift* consists of a small, almost constant lift of the intake valve during the exhaust stroke, so to increase the valves overlapping. The results show a benefit on the fuel economy and on the gas-dynamic noise at part load and a substantial increase in the delivered torque at full load, while preserving the fuel consumption.

Keywords: 1D engine modeling, VVA, *pre-lift* valve strategy, fuel consumption, gas-dynamic noise, engine performance

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Nomenclature

1D	one-dimensional
BSFC	Brake Specific Fuel Consumption
BMEP	Brake Mean Effective Pressure
DI	Direct Injection
EIVC	Early Intake Valve Closure
EGR	Exhaust Gas Recirculation
ICE	Internal Combustion Engine

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MFB	Mass Fraction Burned
PID	Proportional Integrative Derivative
SPL	Sound Pressure Level
SI	Spark Ignition
TDC	Top Dead Center
VVA	Variable Valve Actuation
h	Pre-lift height
$\Delta\theta$	Pre-lift duration
φ_2	Intake valve closure angle

1. Introduction

The modern automotive Internal Combustion Engines (ICEs) are characterized by more and more complex architectures in order to minimize the fuel consumption, without penalizing power and torque performance, and to comply with the European law concerning the pollutants and CO_2 emissions [1]. To this aim, regarding the Spark Ignition (SI) ICEs, a common strategy involves the reduction of the total displacement and the coupling to a turbocharger [2].

This approach, usually named *downsizing*, allows for the required performance target and a reduction of the fuel consumption at part load with respect to a naturally aspirated engine delivering the same power. In fact, for an assigned load level, a smaller displacement determines a reduced throttling of the intake system, with a positive effect on the pumping work [1],[2]. In addition, a smaller displacement and weight imply lower mechanical losses.

The downsizing benefits at part load can be further enhanced equipping the engine with a fully flexible valve actuation system. The valve actuation systems currently available on the market allow for the variation of the phasing, [3],[4],[5] or, in addition, of the lift (VVA – Variable Valve Actuation) [6],[7]. The aim of both the solutions is the load adjustment with a reduced or, even, absent butterfly valve throttling; this implies, as said before, a significant positive influence on the pumping work.

The small size does not undermine the ICE power and torque performance at full load operations thanks to the possibility to proper increase the boost pressure. However, some drawbacks usually arise in terms of fuel economy in these operating conditions. In fact, a very common problem for the turbocharged engines is the attainment of very high in-cylinder pressure and temperature levels that determine an increased risk of knocking combustions.

To overcome the above issue, a usual solution is the delay of combustion phasing, often very late after the TDC. This methodology once again has a negative impact on the engine BSFC. In addition, it causes the attainment of high temperature levels at the turbine inlet that, on the contrary, have to be limited because of the turbine blades safety. The above limitation is widely faced by an enrichment of the air-to-fuel ratio of the mixture that has the aim to employ the heat absorbed by the fuel evaporation to reduce the in-cylinder temperature levels. This solution further contributes to avoid the knock risk, but, on the other hand, has an additional negative impact on the fuel economy.

If a direct injection (DI) system is used, the fuel evaporation takes place in the cylinder. This occurrence, in addition the increased knock resistance [8], gives the opportunity to avoid any substantial loss of fresh fuel through the exhaust system during the scavenging process. This allows for a higher intake/exhaust valves overlap, with direct advantages in terms of cylinder scavenging. In some cases, the direct injection is employed to realize a stratified charge in the cylinder with the aim of improving the combustion process and, as a consequence, reducing the fuel consumption by using lean air/fuel mixture [9].

The analyses discussed in the present paper concern a prototypal four-cylinder turbocharged DISI ICE (Table 1) equipped by a fully flexible actuation system for the intake valves. Its flexibility is due to an electro-hydraulic system belonging to the lost motion family [10], [11]. The use of a VVA system to adjust the engine load implies, as previously mentioned, a reduction in the pumping work, but, at the same time, a deterioration in the engine performance in terms of gas-dynamic noise radiated at the intake mouth [12]. In fact, the lower intake throttling involves a less effective damping of the pressure waves moving through the intake ducts.

Table 1 – Engine main characteristics

Model	Turbocharged, 4 cyl., 16 valves, VVA
Displacement	1368 cm^3
Stroke/Bore	84 mm / 72 mm
Connecting Rod Length	128.95 mm
Compression Ratio	10

In this work, the effects of an unconventional valve strategy, named *pre-lift* [13], are numerically investigated by means of a 1D approach, both at part and full load operations. A *pre-lift* consists of a small lift of the intake valve during the exhaust stroke.

In a first stage, the model is integrated within a commercial multi-purpose optimization software (modeFRONTIER™) [14], to identify the engine calibrations able to optimize the BSFC and the gas-dynamic noise emissions at 2000 rpm and 2 bar of BMEP (in the following labelled as 2000@2) with a conventional Early Intake Valve Closing (EIVC) strategy. Then, the same automatic procedure is used to estimate the effects of the introduction of a *pre-lift*. Finally, the potentialities of the proposed unconventional valve lift strategy are also studied at full load operations, with the aim to improve the engine performance and the fuel economy.

2. Model description and tuning

The engine model is implemented within the GT-Power™ commercial software. The combustion process and the turbulence phenomenon are described by "in-house developed" sub-models. Specifically, the combustion process is modeled by the "fractal combustion model" [15], [16]. The turbulence phenomenon is described by a 0D sub-model capable to sense the valve opening and closing timing [17]. The combustion process modeling is properly linked to the in-cylinder turbulence evolution in order to detect the effects of different control settings on the engine performance.

The valve lift profiles used in the simulations are derived by a 1D model of the electro-hydraulic valve actuation system. Typical lift profiles are depicted in Fig. 1. The latter also shows a *pre-lift* [13], characterized by its duration, $\Delta\theta$, and height, h.

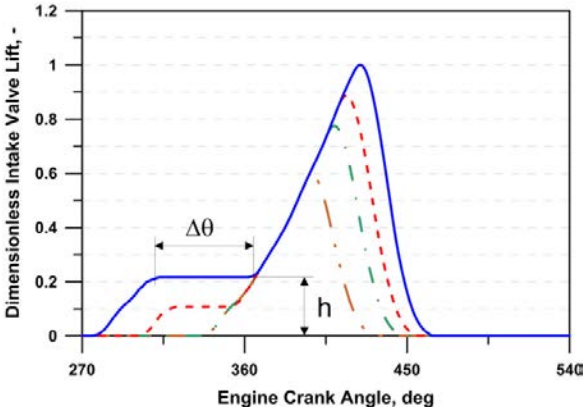

Fig. 1. Typical valve lift profiles with different *pre-lift* and closure angles

The 1D schematization of the tested engine includes a "virtual microphone object" located at 1 cm from the intake orifice [18]. It is used to detect the gas-dynamic noise in terms of Sound Pressure Level (SPL).

The knock intensity is computed by a chemical kinetic solver (CHEMKIN), able to detect the presence of autoignition phenomena in the end-gas. To this aim, a reduced kinetic mechanism (5 elements, 32 species, 55 reactions) for the oxidation of iso-octane and n-heptane mixtures is specified [19],[20],[21].

Since the design of the analyzed engine is not completely concluded, experimental data are not yet available. Nevertheless, the combustion and turbulence sub-model tunings are borrowed by an engine of the same family. All the details about the similar engine and the sub-models tuning are included in [14], [16], [17].

3. *Pre-lift* optimization at 2000@2

A virtual engine calibration is performed by an automatic procedure, implemented within a commercial optimizer. It includes the 1D engine model and has the aim to identify the strategies that minimize the BSFC and the SPL at 2000@2. In particular, two optimizations are carried out: in the first one, the decision variables are the waste-gate opening and the intake valve closure angle, φ_2; in the second optimization, the decision variables also include the *pre-lift* duration and height (Fig. 2a).

A PID controller, implemented in the 1D model, allows to identify the throttle valve opening required to get the target BMEP of 2 bar. The simulations are carried out by searching the spark advance, so that the combustion center phasing reaches a literature advised value of 8 degrees after TDC. An injector adjusts the fuel amount according to the air flow rate, in order to realize a stoichiometric air-to-fuel ratio. At the end of each simulation, the optimizer uses the computed BSFC and SPL levels to update the decision variables for the next iteration according to a genetic algorithm logic.

Previous works have already demonstrated that the described optimization procedure is able to identify numerically with great accuracy the experimentally applied strategy realizing the lowest BSFC [14]. With reference to the considered engine, the trade-off between BSFC and SPL has been found in [13] for the analyzed operating point. In Fig. 2b, the Pareto frontier is here repeated, with and without the application of the *pre-lift* strategy.

Because of the confidentiality required by the engine manufacturer, all the proposed quantities are normalized by subtracting the corresponding values of the solution that realizes the minimum BSFC in absence of a *pre-lift*. The latter is labeled “0”, and is assumed as reference solution. The results highlight that the introduction of a *pre-lift* provides a significant reduction in the BSFC (10 g/kWh as shown in Fig. 2b), attaining its minimum value in the condition labeled “B”. Among the optimal solutions, the calibration realizing the minimum gas-dynamic noise (labeled “N”) is selected, too.

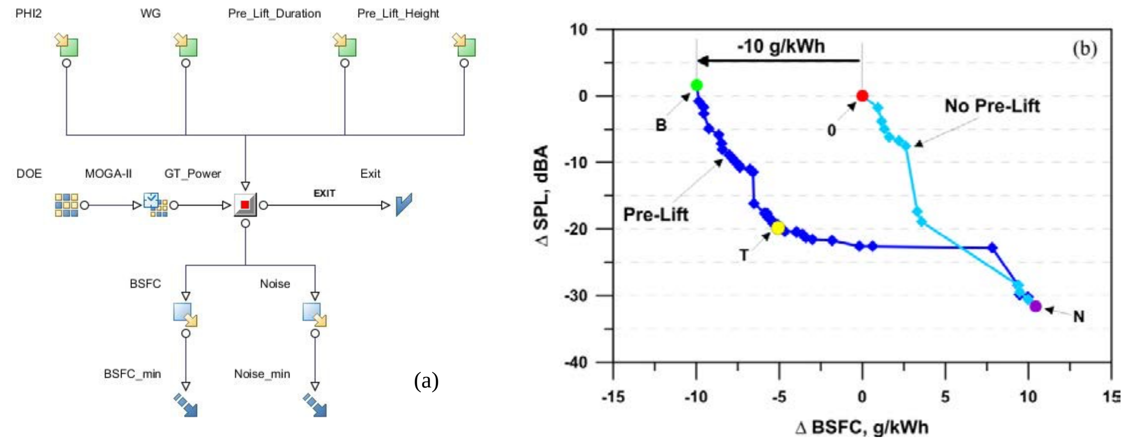

Fig. 2. (a) Workflow of the optimization process including the *pre-lift* design parameters; (b) Comparison between the Pareto optimal fronts for the strategies with and without *pre-lift* [13]

Fig. 2b shows a comprehensive picture of the engine behavior at the prescribed operating point. In [13], it has been shown that the main path to reduce the fuel consumption through a *pre-lift* (solution “B”), with respect to a classical EIVC (solution “0”), is the promotion of an internal EGR, thanks to the prolonged valves overlapping. This allows for a delayed valve closure, that determines a higher volumetric compression ratio and an improved thermodynamic efficiency.

A part from the best BSFC configuration, it is possible to carry out the selection of some solutions that represent a compromise between the two considered conflicting objectives. As an example, a particularly interesting solution is “T” (Fig. 2b), that guarantees a substantial reduction in SPL (-20 dBA), with respect to the optimized EIVC strategy “0”, while ensuring an adequate improvement in BSFC (-5 g/kWh). Fig. 3 shows that solution “T” is characterized by a *pre-lift* height equal to the best BSFC solution “B”, while its duration is almost one half of “B”.

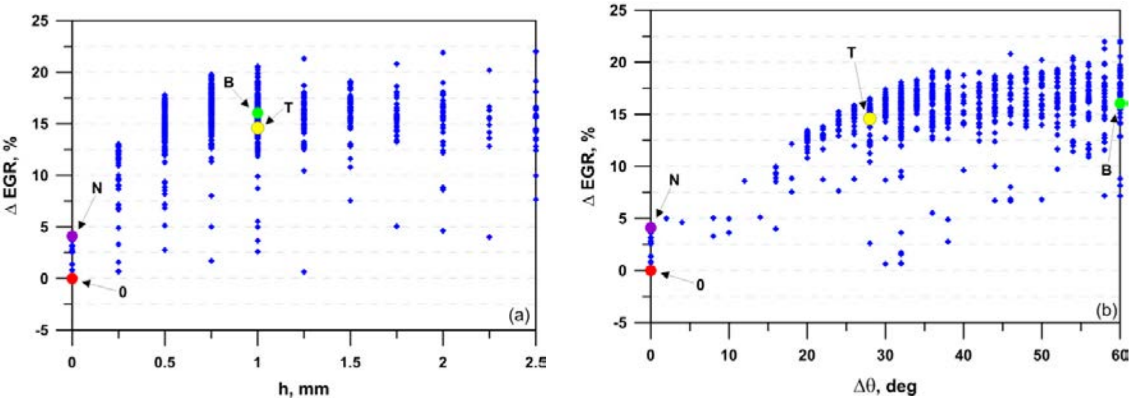

Fig. 3 (a) ΔEGR fraction vs. maximum *pre-lift* height; (b) ΔEGR fraction vs. *pre-lift* angular duration

Focusing on the gas dynamic noise performance, the closure level of the throttle valve, as expected, strongly affects the damping of the pressure waves traveling along the intake system and, consequently, the radiated noise. The comparison between Fig. 4a and Fig. 4b, that show the instantaneous pressure downstream and upstream the throttle valve respectively, puts into evidence that the more effective pressure wave attenuation is obtained for the solution “N”, while a satisfactory result is achieved for the compromise solution “T”. On the other hand, the worst results are obtained for the optimal BSFC solutions “B” and “0”, when an almost completely opened throttle valve is applied. It is not worthless to emphasize that the best solution in terms of noise emission is obtained in absence of *pre-lift* (Fig. 3a). In the latter case, the high frequency pressure fluctuations are fully damped, as a consequence of the close-to-sonic flow through the throttle valve. The same occurrence does not verify for the solutions “0” and “B” where, indeed, high frequency pressure fluctuations propagate along the whole intake system, up to the intake mouth, causing a very high gas-dynamic noise.

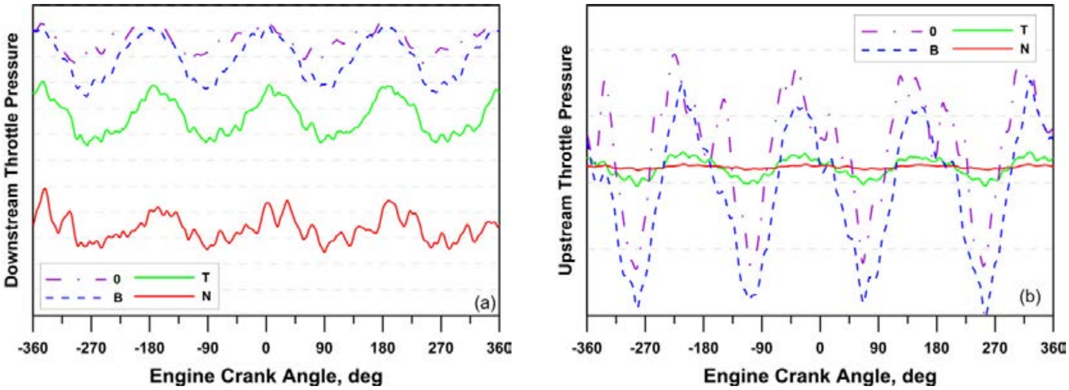

Fig. 4. Instantaneous pressure downstream (a) and upstream (b) the throttle valve for the selected solutions at 2000@2

4. ***Pre-lift*** application at full load operations

At full load operating conditions, a positive pressure gradient between the intake and exhaust systems is usually available during the valves overlapping, especially for the lower speeds. The aim of this section is to investigate the possibility to properly employ the above occurrence through an increased duration of the valves overlapping. This is realized through a *pre-lift* of the intake valve. In particular, the same *pre-lift* design (duration and height) derived in the above part load study minimizing the fuel consumption (solution "B") is also applied in the following full load analyses.

In a first stage, the engine performance are evaluated in absence of a *pre-lift* (in the following labelled as "base"). In Fig. 5, the so-called "pumping loop" is depicted for the speed of 2000 rpm. It shows the instantaneous in-cylinder, intake and exhaust pressures together with the valves lifts. It can be noted the presence of a relevant pressure gradient between the intake and exhaust pipes, but it mainly verifies when the intake valve is closed. As a consequence, the above pressure gradient cannot be employed to promote a more effective cylinder scavenging.

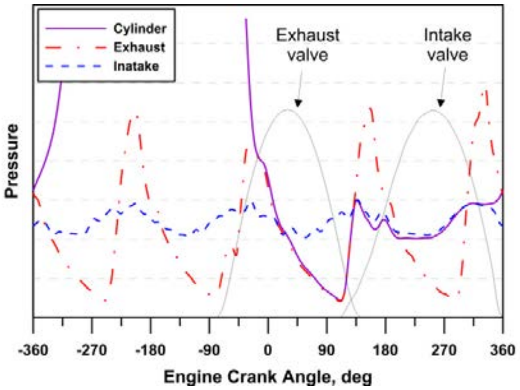

Fig. 5. Pumping loop in absence of a *pre-lift* at full load and 2000 rpm

In a second stage of the analysis, the introduction of a *pre-lift* is studied for the same boost pressure and knock intensity of the base case. In particular, two engine configurations are investigated: the first one (labelled as "Power") where the air to fuel ratio is maintained equal to the base case, the second one (labelled as "BSFC") where the fuel amount is adjusted through a PID controller to maintain the same turbine inlet temperature as the base case. To guarantee the same knock level, a further PID controller is introduced in the model that properly adjust the spark advance.

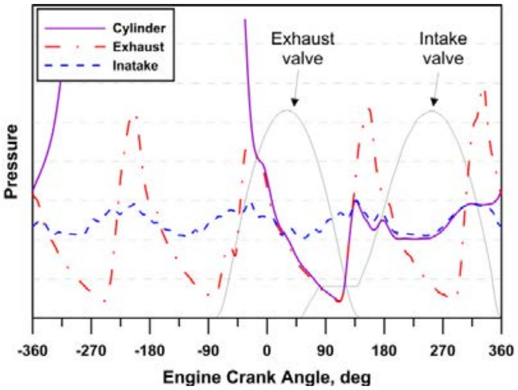

Fig. 6. Pumping loop in presence of a *pre-lift* at full load and 2000 rpm (Power condition).

With reference to the configuration “Power” for a speed of 2000 rpm, the pumping loop is depicted in Fig. 6. It is confirmed the presence of a positive intake/exhaust pressure gradient, but now it can be properly employed thanks to the *pre-lift* adoption.

Fig. 7 shows the effect of the proposed valve lift strategy in terms of the effective volumetric efficiency[†]. The latter puts into evidence that an improved cylinder filling is obtained with respect to the base configuration for the speeds of 1750, 2000 and 3000 rpm. For the higher speeds, the increased flow losses and the inefficient operations of the turbine cause a rise in the mean exhaust backpressure; consequently, a negative pressure gradient between the intake and the exhaust occurs and no improvement in the cylinder scavenging can be realized. The *pre-lift* adoption does not induces any benefit on the cylinder filling also for the lowest considered speed of 1500 rpm. In fact, in this operating condition, a prolonged overlapping promotes a backflow through the intake valves that affects the trapping of fresh air. A direct consequence of the improved cylinder scavenging is the increase in the delivered torque (Fig. 8a) for the medium speeds (2000 and 3000 rpm), while reducing the fuel consumption at the same time (Fig. 8b).

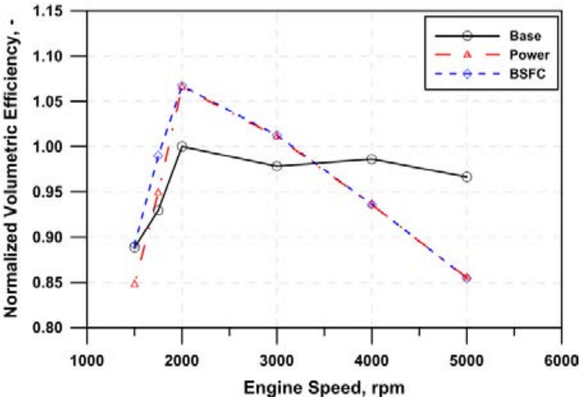

Fig. 7. Comparison of effective (trapped) volumetric efficiency at full load operations

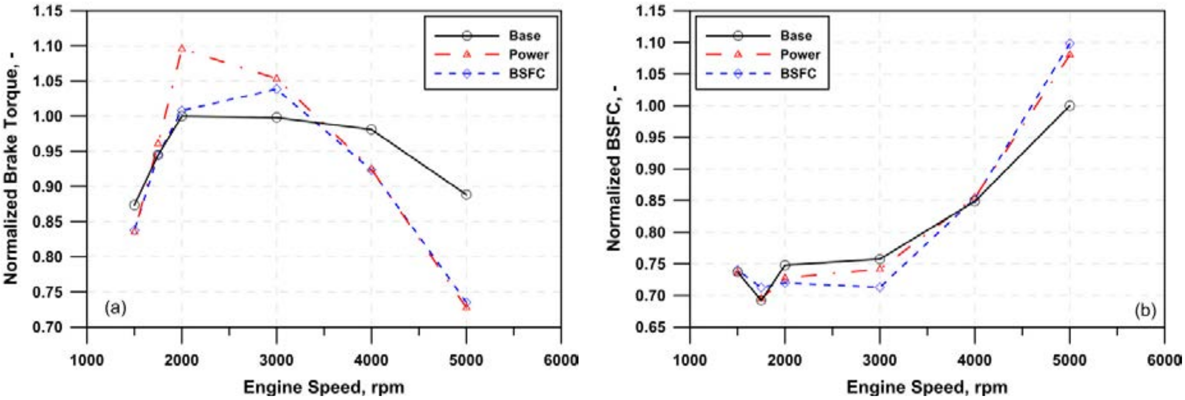

Fig. 8. Comparison of brake torque and BSFC at full load operations

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[†] Because of the confidentiality of the plotted data, all the quantities in Fig. 7-Fig. 10 are normalized with the maximum values attained in the base configuration, excepting the MFB50% that is represented as difference between the actual value and the maximum one applied in the base configuration

The differences between the “Power” and “BSFC” configurations are mainly due to different air-to-fuel ratios and combustion timings. The plots of the above quantities are depicted in Fig. 9a and Fig. 9b, respectively. It can be noted that, as expected, the better fuel economy is achieved when an air/fuel mixture leaning is realized. However, in the “BSFC” calibration, a certain combustion phasing delay has to be admitted to avoid the knock onset, for the cases at 1500, 1750 and 2000 rpm. This occurrence partially mitigates the BSFC advantages related to the higher air-to-fuel ratio. On the contrary, higher performance can be attained by the “Power” solution, thanks to an advance in the combustion process towards the TDC (about 3 degrees at 2000 rpm).

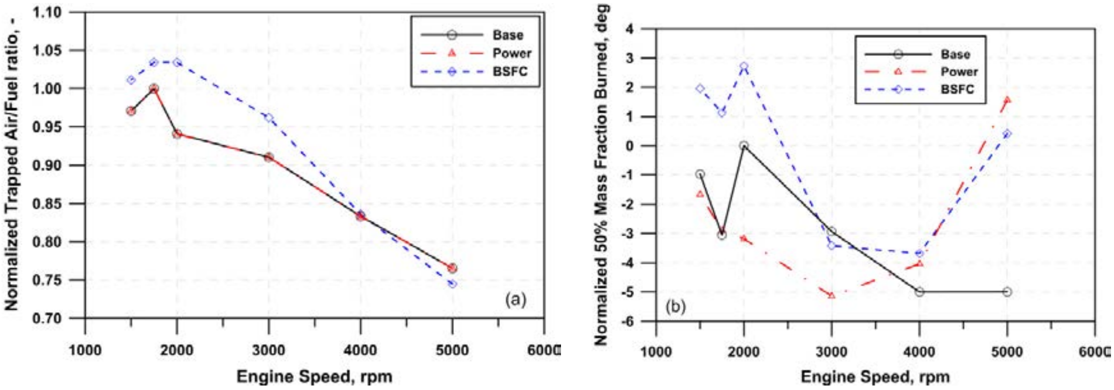

Fig. 9. Comparison of trapped air-to-fuel ratio and of MFB 50% at full load operations

The second main effect of the *pre-lift* strategy is a short-circuiting of fresh charge form the intake towards the exhaust during the prolonged overlapping. As expected, this induces a substantial reduction in the turbine inlet temperature. The consequence of the above mechanism is clearly pointed out in the Fig. 10, where a reduced turbine inlet temperature occurs in the “Power” configuration with respect to the base one. On the contrary, for the “BSFC” calibration, the turbine inlet temperature reaches higher levels, similar to the base configuration ones, because of the air/fuel mixture leaning.

Summarizing, the *pre-lift* adoption shows the potential to improve the engine performance and fuel economy at full load operations for the medium speeds of 2000 and 3000 rpm, without penalizing the fuel consumption.

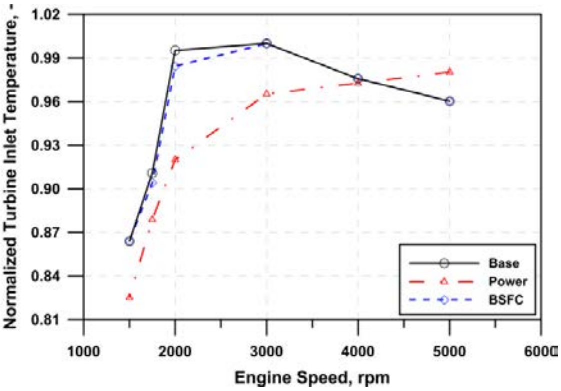

Fig. 10. Comparison of turbine inlet temperature at full load operations

5. Conclusions

The paper describes a numerical study about the effects of an innovative intake valve *pre-lift* strategy applied to a turbocharged internal combustion engine equipped with a fully flexible VVA system. The engine model is developed in GT-Power environment and is provided of user routines for the turbulence/combustion description.

In a first stage, the model is included in the commercial optimization software ModeFRONTIER, with the aim of identifying the calibration strategies that minimize the fuel consumption and the gas-dynamic noise emissions in a part-load point, 2000@2, both in presence and absence of a *pre-lift*. The optimizer identifies the trade-off between BSFC and SPL, and highlights the benefits due to a *pre-lift* strategy with respect to the more conventional EIVC.

The potential of the *pre-lift* strategy is studied at full load operations, too. It is shown that the proposed valve lift strategy can be used to better employ the favorable pressure gradient between the intake and the exhaust available at some low/medium engine speeds. The prolonged valves overlapping allows for an improved cylinder scavenging and an increase in the delivered torque, while reducing the fuel consumption.

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