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Performance Optimization of a Turbocharged Spark-Ignition VVA Engine at Part Load

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Abstract: Nowadays, modern internal combustion engines show more and more complex architectures in order to improve their performance. Referring to the spark-ignition (SI) engines, downsizing philosophy and Variable Valve Actuation (VVA) systems allow to reduce the Brake Specific Fuel Consumption (BSFC) at low and medium load, while maintaining the required performance at high load. On the other hand, the above solutions introduce additional degrees of freedom for the engine control, requiring longer calibration time and experimental effort.

In the present work, a twin-cylinder turbocharged VVA SI engine is numerically investigated by a one-dimensional (1D) model (GT-Power™). The considered engine is equipped with a fully flexible VVA actuation system, realizing an Early Intake Valve Closure (EIVC) strategy. Proper “user routines” are implemented in the code to simulate turbulence and combustion processes.

In a first stage, 1D engine model is validated against the experimental data under part load condition, both in terms of overall performance and combustion evolution. The validated 1D engine model is then integrated in a multipurpose commercial optimizer (mode FRONTIER™) with the aim to identify the engine calibrations that simultaneously minimize BSFC and Brake Mean Effective Pressure (BMEP) under part load operation at a specified engine speed of 3000rpm. In particular, the decision parameters of the optimization process are the EIVC angle, the throttle valve opening and the waste-gate valve opening and combustion phasing. Proper constraints are assigned for the pressure in the intake plenum in order to limit the gas-dynamic noise radiated by the intake mouth.

The adopted optimization approach shows the capability to reproduce with a very good accuracy the experimentally advised optimal calibration, corresponding to the numerically derived Pareto frontier in the Brake Mean Effective Pressure (BMEP)-BSFC tradeoff. The optimization also underlines the advantages of an engine calibration based on a combination of EIVC strategy and intake throttling, rather than a purely throttle-based calibration.

The developed automatic procedure allows for a “virtual” calibration of the considered engine on completely theoretical basis and proves to be very helpful in reducing the experimental costs and the engine time-to-market.

Keywords: 1D engine modeling, optimization, VVA, SI engine.

1. INTRODUCTION

Modern spark ignition internal combustion engines are characterized by different sub-systems aiming to improve the performance in terms of both power/torque, fuel consumption, pollutant emissions and radiated noise. Among the various innovative solutions, turbocharging technique and completely flexible valve actuation systems are currently the most promising technologies for further improvements. Initially, valve actuation systems were only used to control the intake and/or exhaust valve phasing (VVT–Valve Variable Timing) [1-3] or employed to realize different cam profiles according to the engine speed [4, 5]. Most recent systems are able to independently define the valve opening, closing and the lift (VVA–Variable Valve Actuation) [6, 7]. The flexibility offered by VVA systems allow to adjust the engine load with a limited throttle valve closing [8, 9], which significantly reduces the pumping work at low/medium load. Moreover, a reduction in nitric oxides (NO_x) emissions or an improved combustion stability at idle were experimentally verified by increasing or reducing the valve overlap, respectively [10-14].

Conversely, while in the past turbocharging systems were used to increase the delivered power and torque, currently it is primarily employed to reduce fuel consumption and, consequently, carbon dioxide (CO_2) emissions [15], thanks to the so-called downsized architecture. It consists in the engine displacement reduction to achieve fuel consumption improvements, due to the lower mechanical and pumping losses. The required power/torque performance for the downsized engine is restored by employing a turbocharger group [16]. Further advantages of downsized engines are related to a higher torque at low engine speed and thus to a better vehicle drivability [17].

The above technologies are included in the engine analyzed in the present paper. The latter is a small turbocharged twin-cylinder engine equipped with a VVA module, able to control the intake valve lift profile. The valve actuation is provided by an electro-hydraulic

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system that modulates the valve lift according to the operating conditions. The system consists of a small capacity between the cam and the valve filled with lubricant oil, whose emptying is regulated by an electronically controlled electro-valve.

Table 1a: Main Engine Data

Model	2 cylinders, 8 valves, VVA
Displacement	875cm^3
Stroke/Bore	86mm / 80.5mm
Connecting rod length	136.85mm
Compression ratio	9.9
Max Brake Power	64.6kW @ 5500rpm
Max Brake Torque	146.1Nm @ 2500rpm

The engine under study, whose main features are listed in the Table **1**, allows to operate in a specified speed-load point using different control strategies. In particular, it is possible to independently define the following parameters:

- α air to fuel ratio;
- β throttle opening angle;
- θ spark ignition timing;
- φ_1 intake valve opening angle;
- φ_2 intake valve closure angle;
- WG turbine waste-gate valve opening.

α, β, and θ are traditionally used to calibrate a naturally-aspirated SI engine, while φ_1 and φ_2 and WG are related to the control of VVA and turbocharger system, respectively. To identify the set of parameters allowing to achieve the required engine performance targets (minimum fuel consumption and pollutant emissions at part load, maximum power and torque at full load, combustion stability at idle, etc.), Design of Experiment (DoE) methodologies are successfully used to limit the number of experimental tests [18].

A further reduction in the experimental activity can be obtained using proper numerical models that, once tuned, are able to achieve an engine pre-calibration following a fully-numerical approach. Activity at test-bench can, hence, be limited to verify and refine the desired performance targets.

In this paper, an example of the methodology described above is discussed in detail. In a first stage, a 1D engine model is validated at part load. It presents the capability to predict the main overall engine performance and combustion parameters with good accuracy. Subsequently, the engine model is included in a general purpose optimizer (mode FRONTIER^{TM}) that is used to identify the calibration parameters that minimize the Brake Specific Fuel Consumption (BSFC) at each Brake Mean Effective Pressure (BMEP) level [19, 20]. Analyses are limited to part load operation for an engine speed of 3000rpm. The proposed optimization procedure allows to find the best compromise among the previously selected objectives, highlighting the advantages of a VVA strategy with respect to a more traditional throttle-based approach.

2. MODELS DESCRIPTION

1D engine model is developed within GT-Power^{TM} commercial code, based on a one-dimensional description of the flow inside the intake and exhaust pipes and a zero-dimensional description of in-cylinder thermodynamic properties. Combustion and turbulence phenomena are modeled using proper sub-models introduced in code through “user routines”. In particular, the combustion process is modeled by adopting the “fractal combustion model” [21-24], which is a phenomenological model sensing both the combustion system geometry (head and piston shape, spark plug position, etc.) and the operating parameters (spark advance, air to fuel ratio, etc.). Turbulence is described by a sub-model [25] capable to sense the valve opening and closure timing, allowing to take into account the variations in the burning speed according to the valve control settings. Different valve strategies can be realized by the valve actuation system equipping the tested engine, including LIVO (Late Intake Valve Opening), EIVC (Early Intake Valve Closure), a combination of the previous ones and a multi-lift strategy. In order to simplify the engine

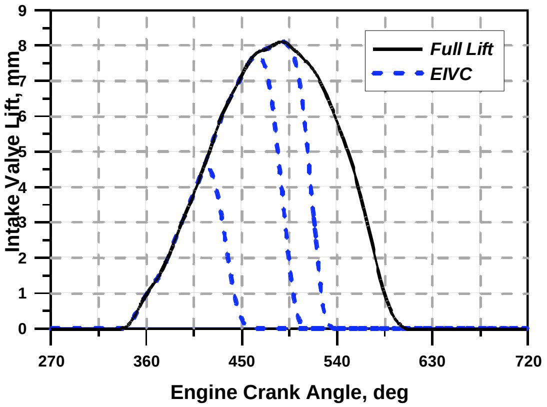

Figure 1: Typical intake valve lifts for Full Lift and EIVC strategies.

calibration issue, among the various available strategies, only the EIVC strategy is taken into account. The Figure **1** shows the comparison between valve lift profiles related to different closure angles.

Employing a hydraulic model of the valve actuation system, different valve lift profiles are calculated for various engine speeds and φ_2 values. These data constitute a valve lift "database" that is used by a "user routine" within GT-Power code to evaluate by interpolation the actual lift profile, depending on the engine operating condition.

A special attention is devoted to the heat transfer modelling because of its critical influence on fuel consumption prediction. A modified Hohenberg correlation is adopted, while the piston, cylinder liner and head temperatures are calculated by the finite element approach implemented in GT-Power code. The heat transfer coefficients on the coolants side (water and oil) are derived by dedicated simulations of the coolant circuit and properly adjusted according to the engine speed, following the approach described in [26].

3. MODEL TUNING

Turbulence and combustion models have been widely validated at full load in previous work of the authors [27, 28], both in terms of overall engine performance (BMEP, BSFC, air flow, etc.) and combustion evolution. In this work, the models are validated at part load for an engine speed of 3000rpm. To this aim, the experimentally advised values of the intake valve closure angle, φ_2 and the air-to-fuel ratio, α, are specified as input for the simulations. The spark advance θ, is automatically adjusted by a controller implemented in the combustion model to match the measured angle at 50% of Mass Burned Fraction (MFB_{50}). Since the experimental waste-gate valve opening cannot directly assigned in a 1D simulation, it is indirectly set through a PID controller targeting the measured turbocharger rotational speed. Finally, the experimental BMEP is matched by a further PID controller acting on the throttle valve opening.

Two engine control strategies are investigated: the first one is the classical throttle based approach with a fixed full lift profile for the intake valve (strategy labeled in the following as *Throttled*); the second one also includes the φ_2 angle as control parameter (strategy labeled in the following as EIVC).

The same tuning constants of the turbulence and combustion models suited for full load operation and identified in previous works [27, 28], are here adopted, without requiring any adjustment. Results of Figure **2** and Figure **3** show the numerical/experimental comparison in terms of air flow rate, boost pressure,

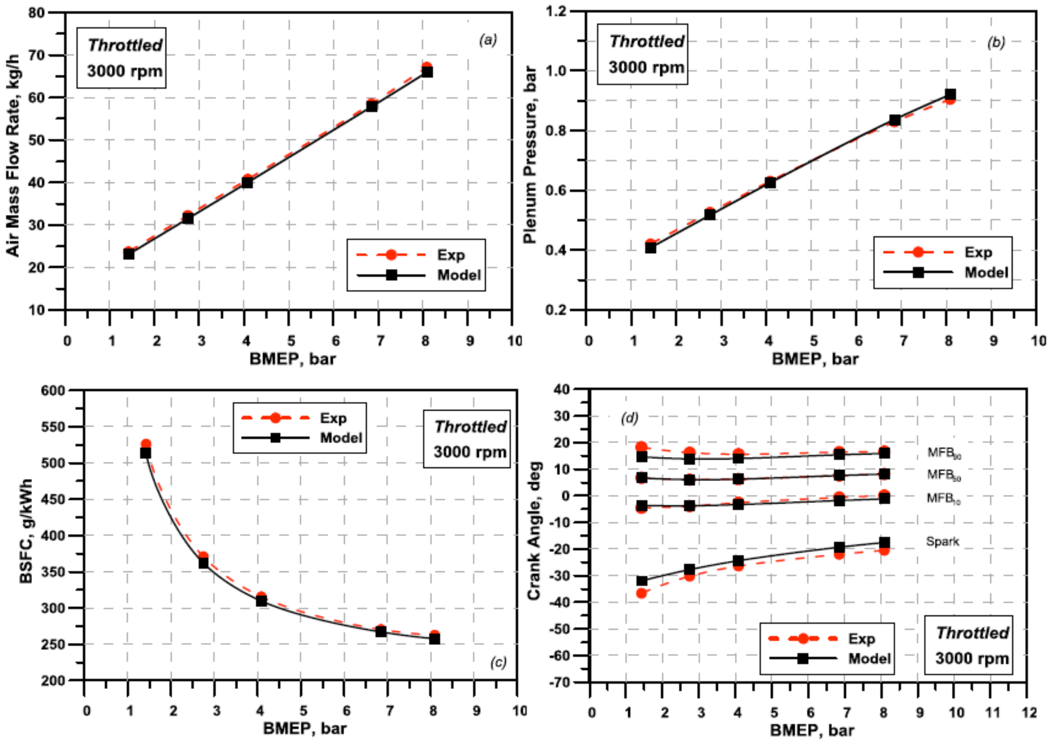

Figure 2: Experimental vs. numerical air mass flow rate, (**a**) plenum pressure, (**b**) BSFC, (**c**) and combustion characteristic angles (**d**) as a function of the BMEP for the Throttled strategy.

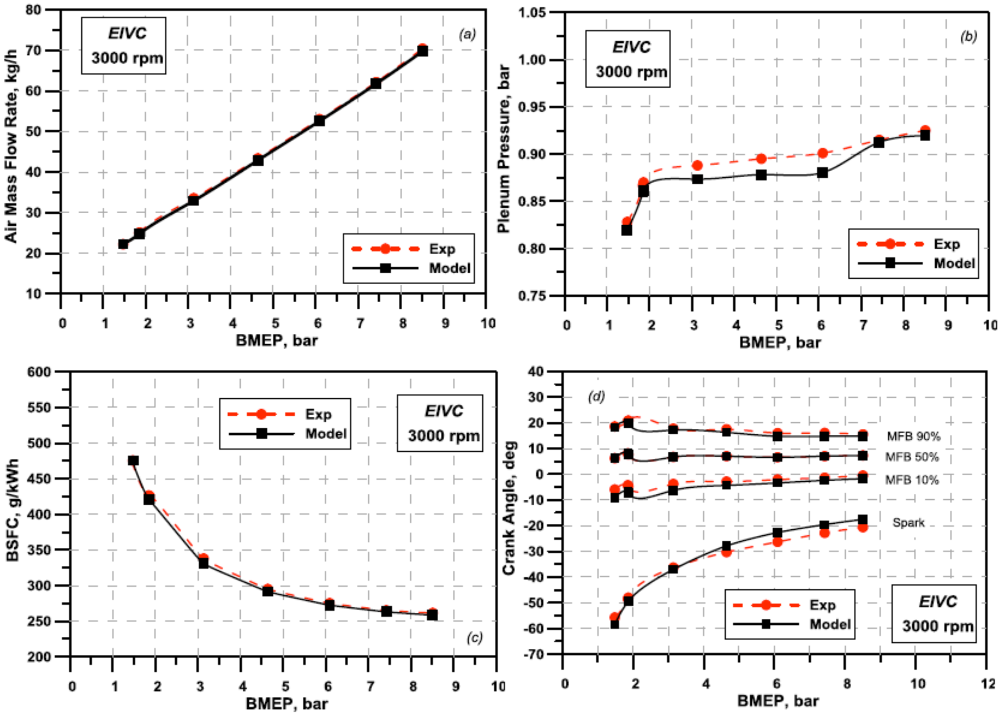

Figure 3: Experimental vs. numerical air mass flow rate (**a**), plenum pressure (**b**), BSFC (**c**) and combustion characteristic angles (**d**) as a function of the BMEP for the EIVC strategy.

BSFC and characteristic combustion angles as a function of the engine load, both for *Throttled* and EIVC strategies, respectively.

The good numerical/experimental agreement in computation of the air flow and pressure in the intake manifold mainly underlines the accuracy of the geometrical schematization of the engine, in addition to the reliability of the turbocharger modelling. The good agreement in the BSFC and combustion findings mainly depends on the accuracy of the adopted combustion and turbulence modelling. In fact, it can be observed that the adopted approach is able to adequately reproduce the combustion lengthening as the load decreases, mainly regarding the early stage of the process (from spark event up to MFB_{10}). This can be ascribed to the capability of the model to sense the reduction in turbulence, temperature and pressure occurring at very part load. This is more true for the EIVC strategy, for which the model is able to correctly locate the spark at 60 CAD before the FTDC at the lowest load level (Figure **3d**).

Of course, the good BSFC prediction is also to be ascribed to the adopted heat transfer model. It is not worthless to underline that the plenum pressure for the EIVC strategy is maintained at an almost constant value of 0.9bar in order to realize a compromise between an acceptable pumping work (requiring a high boost pressure) and a satisfactory pressure wave damping in the throttle valve. The latter occurrence is mandatory to comply with the manufacturer limitations on the gas-dynamic noise radiated by the intake mouth (requiring a low boost pressure).

The above model validation represents a fundamental prerequisite to guarantee the reliability of the optimization procedure described in the next section.

4. OPTIMIZATION PROCEDURE DESCRIPTION

1D model represents the core of the optimization process aiming to define the engine calibration strategy that minimize BSFC at each load level. The parameters for the engine calibration are the throttle valve opening, the intake valve closure angle, MFB_{50} angle and the waste-gate valve opening. The air-to-fuel ratio is fixed at the stoichiometric value, as usually required at part load, in order to ensure proper operation for the catalytic converter.

Figure **4** illustrates the logical scheme of the optimization procedure, developed in the modeFRONTIER graphical environment. The optimizer, which is based on the genetic algorithm MOGA-II, iteratively selects the values of the above listed control parameters that are written in the input file of the 1D model. Then, a single analysis is performed at the

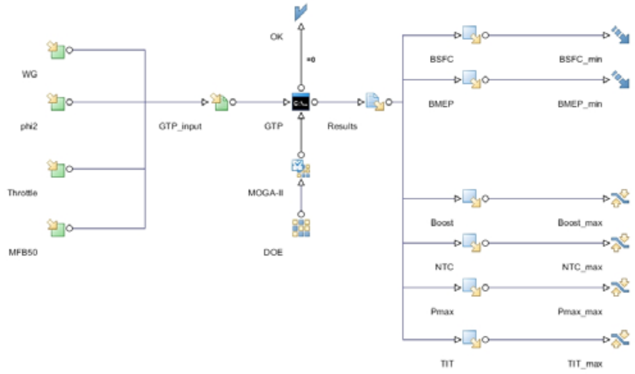

Figure 4: Flowchart of the optimization process implemented in mode FRONTIER environment.

predefined engine speed of 3000rpm. At the end of each simulation, the computed BSFC and BMEP are passed back to the optimizer for the next iteration, until optimal values are identified. Proper constraints are imposed for the plenum pressure (0.9bar), turbocharger speed (255000rpm), in-cylinder maximum pressure (100bar) and turbine inlet temperature (950 °C). As usual, in a multi-objective optimization, the above search corresponds to the evaluation of the so-called "Pareto-frontier" in the BSFC-BMEP plane, expressing the trade-off between the two objectives and collecting the infinite solutions of the optimization problem. The latter represents the optimal control strategy for the tested engine.

In a second stage, a further optimization is set up, where the φ_2 angle is fixed at a value corresponding to the full valve lift profile. In this way, a classical throttle-based engine calibration is accomplished.

5. RESULTS DISCUSSION

Figure **5a** and Figure **5b** collect all the engine calibrations investigated by the optimizer in the BSFC vs. BMEP plane both for the EIVC and *Throttled* strategies. In the Figures, green rhombuses correspond to engine calibrations respecting the constraints on the maximum allowable plenum pressure, turbocharger speed and turbine inlet temperature (labelled as "Feasible"), while the others, depicted as light blue crosses, represent unfeasible solutions (labelled as "Unfeasible"). The optimal solutions are represented by blue rhombuses; the latter are connected by a blue curve, denoting the Pareto frontier (labelled as "Pareto"). Figure **5a-b** also show the numerical results obtained by imposing the experimentally advised calibration (labelled as "Exp Calibration"), already discussed in the "Model tuning" section.

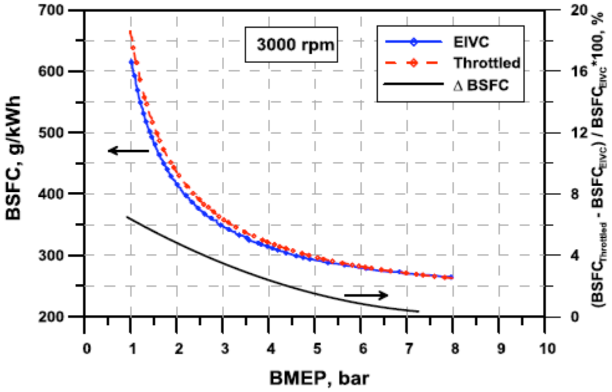

Figure 6: Comparison of Pareto frontiers in the BSFC vs. BMEP for EIVC and *Throttled* strategies.

It can be observed that in each point the Pareto frontier is almost superimposed to the calibration identified at the test bench, denoting the reliability of the proposed optimization procedure. Figure **6** shows an absolute and percent comparison between the considered strategies, showing that a lower BSFC is always obtained for EIVC calibration. It can be observed that the advantages of the EIVC approach are minimum at the medium loads, while they increase as the load decreases, with a maximum advantage of about 6% at 1bar of BMEP. The main driver for the

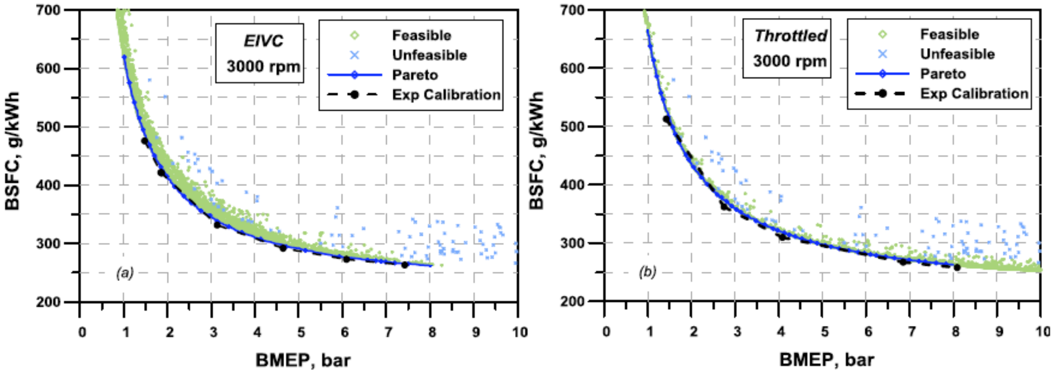

Figure 5: Pareto frontiers in the BSFC vs. BMEP plane for EIVC (**a**) and *Throttled* (**b**) strategy.

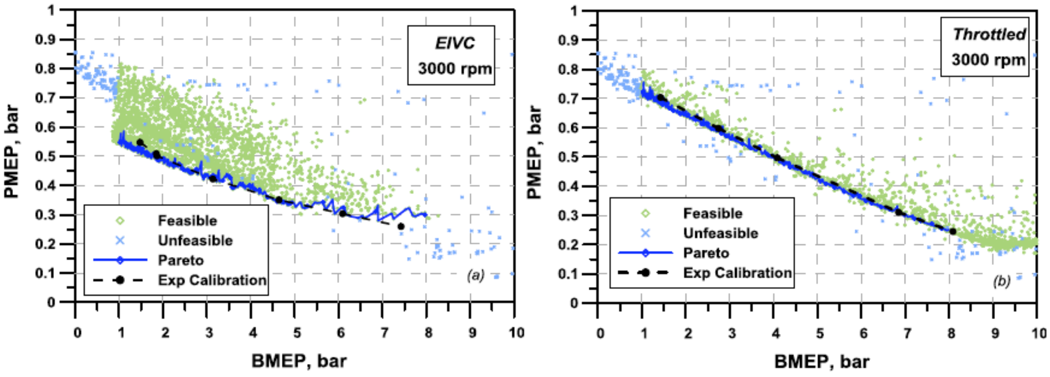

Figure 7: PMEP vs. BMEP for EIVC (**a**) and *Throttled* (**b**) strategy.

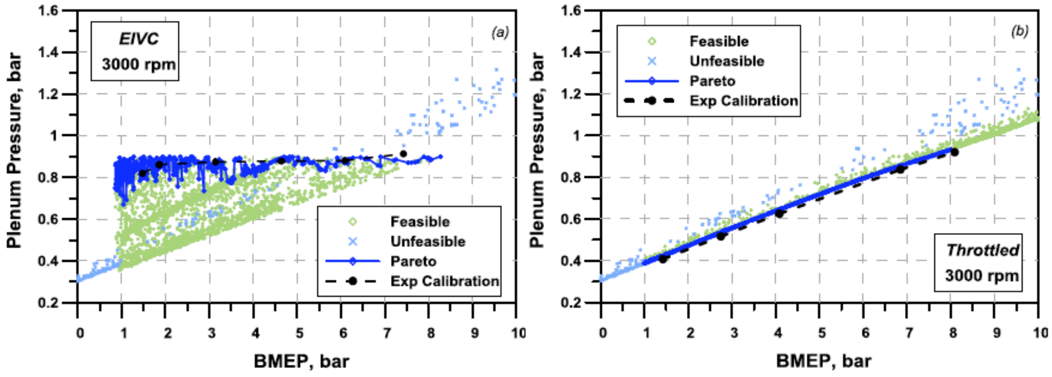

Figure 8: Plenum pressure vs. BMEP for EIVC (**a**) and *Throttled* (**b**) strategy.

BSFC improvements of EIVC strategy is, as expected, a lower pumping work, as shown in Figure **7a**. The above occurrence is ascribed to the possibility to adjust the amount of aspirated air by a modulation of the intake phase duration, rather than on the throttle valve position. This, of course, determines a higher in-cylinder pressure during the intake stroke, and consequently a lower pumping work.

Once discussed the capability of the proposed procedure in the identification of the optimal engine performance at part load operation, in the following the calibration parameters (input variables for the optimization) realizing the optimal performance will be compared with the experimentally actuated values.

Concerning the throttle valve, the angle imposed in the 1D simulation cannot be easily compared with any parameter set in the engine control unit (ECU). For this reason, the numerical/experimental throttle openings are indirectly compared by means of the pressure level in the plenum manifold (labelled as “plenum pressure” in Figure **8**). It can be noted that the operating conditions belonging to the Pareto frontier realize a plenum pressure very close to the one derived by the experimental calibration. Figure **8a** also underlines that an EIVC strategy allows to maintain an high boost level, even at very low engine loads, with significant advantages on PMEP and, consequently, on BSFC. However, the above advantages are limited by the imposed constraints set, as said, at 0.9bar, in order to limit the gas-dynamic noise emission at the intake mouth. The reliability of the optimization process is further confirmed by Figure **9**, showing a very good agreement between the numerically- and experimentally-advised optimal values for the intake valve closure angles.

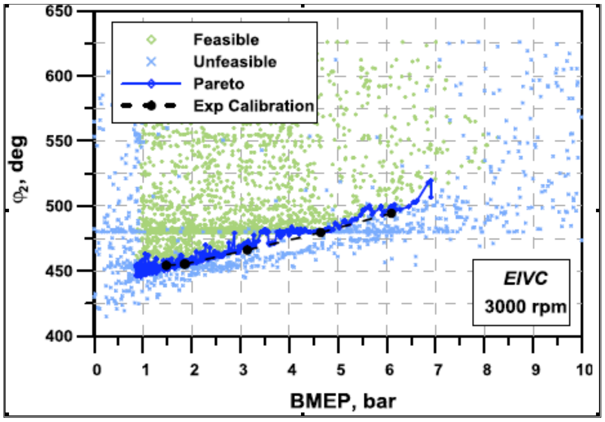

Figure 9: Intake valve closure angle, φ_2, vs. BMEP for EIVC strategy.

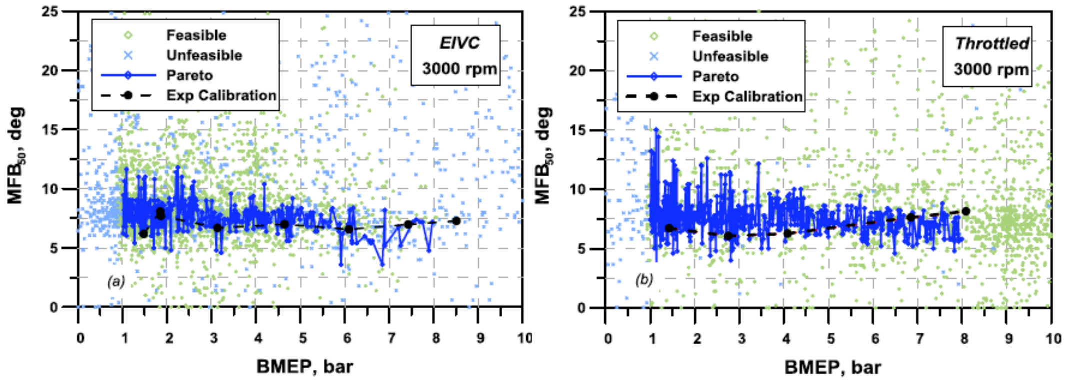

Figure 10: MFB$_{50}$ vs. BMEP for EIVC (**a**) and *Throttled* (**b**) strategy.

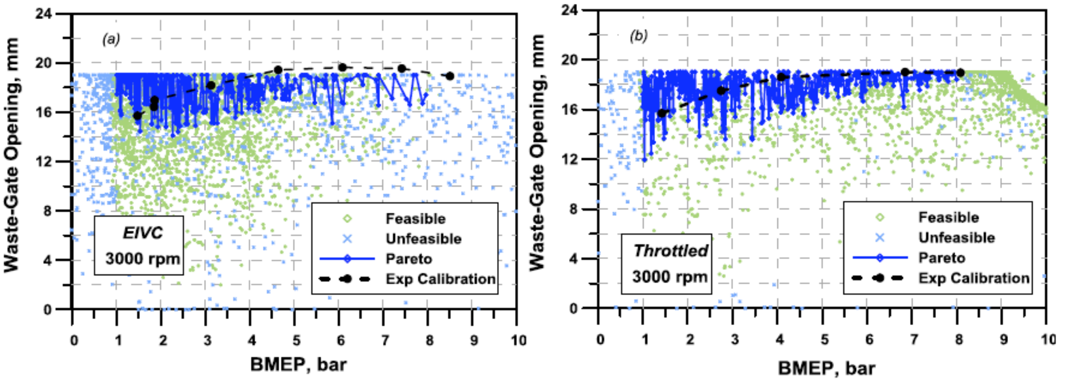

Figure 11: Waste-gate opening vs. BMEP for EIVC (**a**) and *Throttled* (**b**) strategy.

The automatic procedure also underlines that the optimal combustion phasing is attained for both the strategies with a MFB$_{50}$ angle between 6 and 8 CAD after the FTDC, denoting once again a very good agreement with the experimentally advised values (Figure **10**). Finally, the optimization process reveals that the optimal calibrations are characterized by an almost fully opened waste-gate valve, in accordance with the experimental settings (Figure **11**). As said, the experimental WG setting is indirectly derived by the imposition of the turbocharger speed in the validation calculation.

Summarizing, the proposed approach, based on the integration of 1D simulation and optimization tool, showed the potential to perform a calibration of the engine at part load on a purely theoretical basis, contributing to reduce the time and costs of an engine set-up at the test bench.

6. CONCLUSIONS

The paper describes a numerical methodology aiming to calibrate a turbocharged spark ignition internal combustion engine equipped with a fully flexible VVA system applied to the intake camshaft. The engine model is developed in GT-Power environment and is integrated with "user routines" for the turbulence/combustion description. The model is tuned against the experimental data at full load operation and validated at part load, denoting a satisfactory agreement with the experimental findings.

The model is then included in the commercial optimizer modeFRONTIER^{TM} with the aim to search the calibration strategy that minimize the fuel consumption at part load. The optimization process shows the capability to numerically identify the experimentally advised engine calibration in terms of combustion phasing, waste-gate opening, plenum pressure and intake valve closure angle. The optimization is also used to compare a common throttle-based calibration strategy with a more refined EIVC strategy, confirming the BSFC advantages of the latter, especially at very low loads.

The proposed methodology shows the potential to realize a "virtual" engine calibration only based on theoretical basis, contributing to reduce time and costs related to experimental activities at the test bench.

Similar activities are currently under development at full load, with the additional limitation related to the knock occurrence.

NOMENCLATURE

1D	One Dimensional
BSFC	Brake Specific Fuel Consumption
BMEP	Brake Mean Effective Pressure
CAD	Crank Angle Degree
ECU	Engine Control Unit
EIVC	Early Intake Valve Closure
FTDC	Firing Top Dead Center
LIVO	Late Intake Valve Opening
MFB_{10}	10% of Mass Fraction Burned
MFB_{50}	50% of Mass Fraction Burned
MFB_{90}	90% of Mass Fraction Burned
MOGA	Multi Objective Genetic Algorithm
PID	Proportional Integral Derivative
PMEP	Pumping Mean Effective Pressure
VVA	Variable Valve Actuation
VVT	Variable Valve Timing
TIT	Turbine Inlet Temperature
WG	Waste-Gate Valve

GREEKS

	Air to fuel ratio
β	Throttle opening angle
θ	Spark ignition timing
φ_1	Intake valve opening angle
φ_2	Intake valve closing angle

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