

# Optimization of a Supercharged Single Cylinder Engine for a Formula SAE Racing Car

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## ABSTRACT

The paper reviews the development and optimization of a SI high performance engine, to be used in Formula SAE/Student competitions. The base engine is a single cylinder Yamaha 660cc motorcycle unit, rated at about 48 HP at 6000rpm. Besides the reduction of engine capacity to 600cc and the mounting of the required restrictor, mechanical supercharging has been adopted in order to boost performance.

The fluid-dynamic optimization of the engine system has been performed by means of 1D-CFD simulation, coupled to a single-objective genetic algorithm, developed by the authors. The optimization results have been compared to the ones obtained by a well known commercial optimization software, finding a good agreement.

Experiments at the brake dynamometer have been carried out, in order to support engine modeling and to demonstrate the reliability of the optimization process.

## INTRODUCTION

As well known, Formula SAE and its equivalent in the UK (named Formula Student) is a competition among University students who have to design and build and compete with a car complying with specific rules.

As far as the engine is concerned, the technical regulations may be summarized as follows [1].

One or more four stroke engines running on gasoline or E85 may be used, with a total displacement not exceeding 610 cc in all, and the air for all engines must

pass through a single air intake restrictor. This restrictor must be of circular shape, and placed between the throttle and the engine(s). The maximum restrictor diameter is 20 mm for gasoline fueled cars and 19 mm for E85. Any device that has the ability to throttle the engine downstream of the restrictor is prohibited.

Turbochargers or superchargers are allowed, but only if the competition team designs the application (i.e. engines originally equipped with a turbocharger are not allowed to compete with the turbo installed). The restrictor must be placed upstream of the compressor but after the carburetor or throttle valve. The intake air may be cooled with an intercooler. Only ambient air may be used to remove heat from the intercooler system. Air-to-air and water-to air intercoolers are permitted.

The car must be equipped with a muffler in the exhaust system to reduce noise to an acceptable level, that will be measured during a static test. Measurements will be made with a free-field microphone placed free from obstructions at the exhaust outlet level, 0.5 m from the end of the exhaust outlet, at an angle of 45 degrees with the outlet in the horizontal plane. The test engine speed for a given engine will be the velocity that corresponds to an average piston speed of 914.4 m/min. The maximum permitted sound level is 110 dBA, assessed through a fast weighting technique.

The throttle must be actuated mechanically, i.e. via a cable or a rod system. The use of electronic throttle control (ETC) or "drive-by-wire" is prohibited.

Water-cooled engines must only use plain water, glycol-based antifreeze or water pump lubricants of any kind

are strictly prohibited. No agents other than fuel and air may be induced into the combustion chamber.

Most of the competitors adopt 4-cylinder in-line engines, derived from road motorbikes, but in the last years single cylinder engines, typically taken from Cross and Endurance bikes, are gaining popularity [2]. On the one hand, multi-cylinder engines rev at high speed and may easily provide high values of peak power (up to 80-100 HP, when restricted), but they are generally heavy and large. Furthermore, low end torque is difficult to be obtained when the engine is tuned at high revving speed. On the other hand, single cylinder engines are simple, compact and light (30 kg may be saved only for the power-train), but they cannot reach the same level of power. This result is due to several factors. First, off the shelf single cylinder engines with high values of specific power (exceeding 100 HP/l) are generally designed for Cross motorbikes, where the typical capacity is 450 cc, and bore size is close to 100 mm. Since bore is so large, an increase of displacement can be obtained only by enlarging the crank radius, thus reducing top revving speed. Therefore, the crankshaft modification does not enhance performance very much, while it boosts costs and failure probability (it is reminded that all the modifications must be designed by students). Second, single cylinder engines are affected by stronger pressure and velocity pulses across the restrictor, in comparison to multi-cylinder engines (because of the lower frequency of the intake process). As a result, mass flow chocking occurs at lower speeds, limiting engine revolutions.

A possible way to overcome the limitations of the single cylinder engine, while preserving its advantages, is the use of supercharging [14,16,17]. Turbocharging is penalized by the throttle that must be placed at the compressor inlet. Conversely, a mechanical compressor does not stall when throttled, and it has the further advantage of providing a boost pressure almost independent on engine speed. As a result, low end torque may be very high, an issue particularly appreciated by drivers on winding tracks, such as the ones where Formula cars have to compete.

Obviously, matching a supercharging system to an existing engine is not a task to be taken lightly, particularly by a team of students. Besides the design of the gas-dynamic system, a critical issue is the increase of thermal and mechanical stress within the cylinder, as well as on the whole drivetrain. From this point of view, an off-the-shelf Cross engine is not very suitable as a baseline, being designed to endure high revving speed but relatively low IMEP and torque. Endurance motorbike engines, with a capacity of 600-650 cc are, in the authors' opinion, a straighter choice, being generally much heavier and less sophisticated than Cross power units, but also stronger.

The paper reviews the development and optimization of a Formula SAE supercharged single cylinder engine, carried out by the team of the University of Modena and

Reggio Emilia. The base engine is a Yamaha 660cc motorcycle unit, rated at 48 HP at 6000rpm, without restrictor (figure 1). Because of the capacity limits enforced by technical regulations, the engine displacement had to be reduced to less than 610 cc. It was decided to decrease the crank radius, and to design a new and longer connecting rod. In this way, no modification on the engine head, cylinder block or crankcase is required, while higher revving speed may be reached. It is also observed that the reduction of displacement for a given combustion chamber volume makes compression ratio slightly decrease (from 10 to 9.3), without further modifications on the combustion chamber or on the head gasket.

Supercharging has been achieved by means of a small Roots compressor (390cc, 5 kg) driven by a belt, and an inter-cooling air-air system.

The injection system too has been modified, for meeting the higher fuel rates required by supercharging. In order to enhance gasoline atomization within the airflow, the injector has been twinned, and each fuel jet has been carefully oriented toward the valve back (one injector per intake valve).

The fluid-dynamic optimization of the engine system has been performed by means of 1D CFD simulation, coupled to a single-objective genetic algorithm, developed by the authors. The optimization results have been compared to the ones obtained by a well known commercial optimization software.

Experiments at the brake dynamometer have been carried out, in order to support engine modeling and to demonstrate the reliability of the optimization process.



**Figure 1:** The base engine (Yamaha XT660 R)

## ENGINE MODEL VALIDATION

A 1D CFD model of the original engine (Yamaha XT660 R) has been built by using GT-Power [3], a commercial software released by Gamma Technologies and extensively used by the authors.

For the sake of brevity, only the more relevant issues of the model will be described in the paper. Since no specific data were available about combustion, friction losses and the flow through the valves, information has been derived from a database on engines, and with the help of some empiricism. A lot of care has been devoted to the modeling of the muffler, represented as a net of 21 volumes and 10 series of orifices (tail noise is considered a performance parameter, since it is limited by technical regulations).

The calibration of the model parameters has been carried out by comparison with experiments at the dynamometer on the base engine, in the original configuration. The more relevant measured quantities are: engine torque, speed, fuel rate and Air-Fuel Ratio (by means of a UEGO sensor).

After this calibration, the model has been updated to represent the modifications required by the Formula SAE regulations, i.e. with the 20 mm restrictor and the total displacement reduced to 610 cc. Again, a comparison has been made between the results provided by simulation and the values measured at the dynamometer, finding a very satisfactory agreement (this comparison is shown in figure 2).

Obviously, the validated GT-Power model of the naturally aspirated Formula SAE engine is the base on which the model of the supercharged engine has been built.

## ENGINE PARAMETRIC DESIGN

The fluid-dynamic optimization of a supercharged Formula SAE engine is far from trivial, since many conflicting issues must be matched.

First, maximum boost pressure and top revving speed should be accurately defined, in order to meet performance and reliability and fuel efficiency. It is reminded that in Formula SAE, high speed operations at Wide Open Throttle (WOT) are important only in the acceleration test, while they have a very limited use on the track, both in autocross and in endurance competitions (beside the circuit is very windy, the car must also slalom among cones, therefore the engine runs throttled most of the time). The adopted design strategy is to keep compressor delivery pressure in a low-medium range (about 1.5 bar, absolute), but let the engine rev up to 7500 rpm. In this way a high power peak may be reached for a few seconds when needed, while under average operating conditions the engine should be safe against knocking. Furthermore, engine

top rotational speed is very easy to be electronically controlled (through the advance map in the ECU), while boost pressure would require a specific valve.

Low delivery pressure helps fuel economy too, for two reasons: 1) compressor isentropic and volumetric efficiencies are generally better than at high pressure ratios; 2) as a thumb's rule, the higher is boost pressure, the richer must be the air-fuel mixture, in order to keep in-cylinder temperature under control.

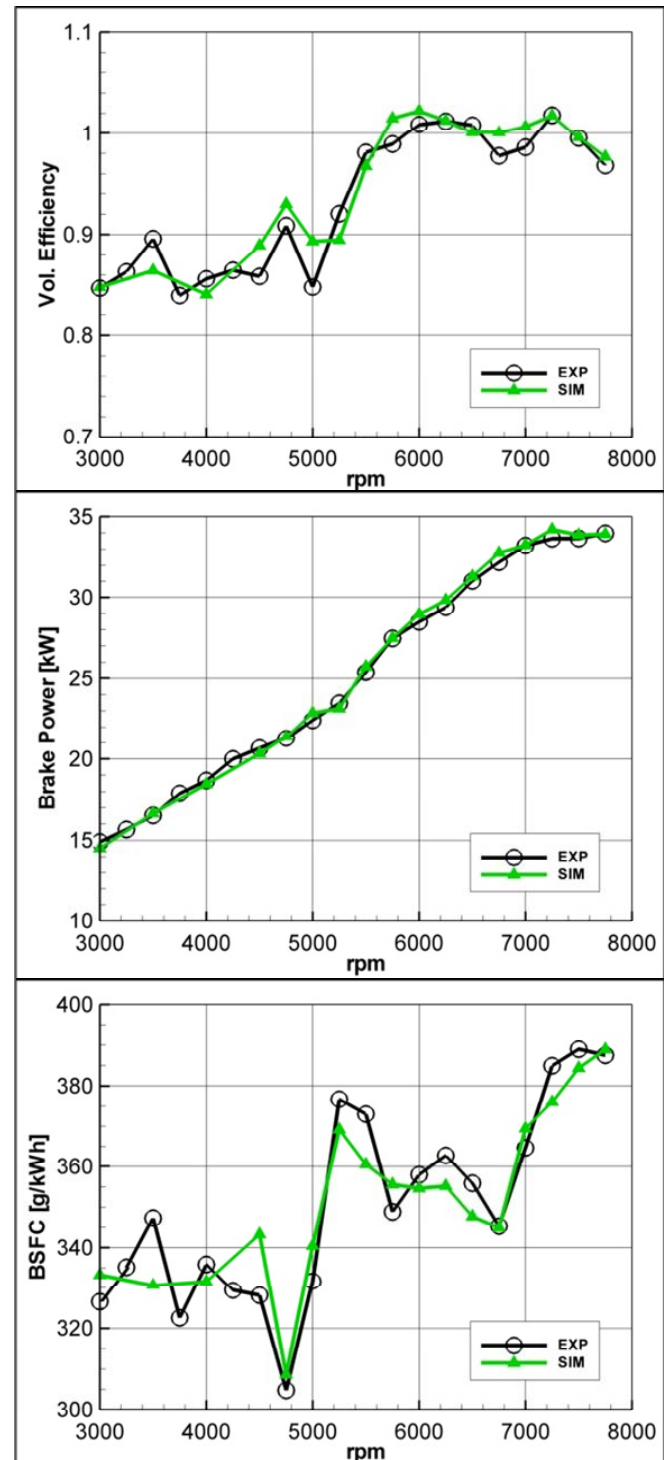


Figure 2: Model validation of the naturally aspirated Formula SAE engine

As well known, for a mechanical supercharging system with intercooler, delivery pressure depends on: ratio of compressor capacity to engine capacity, transmission ratio between engine and compressor, ratio of compressor volumetric efficiency to engine volumetric efficiency (referred to intake port pressure) and intercooler outlet temperature. Therefore, once the choice of compressor and target delivery pressure and intercooler outlet temperature is made, on the base of a number of design constraints, the value of transmission ratio is subsequent.

Another critical issue is the trade-off between flow-dynamic tuning and engine transient response. On the one hand, large volumes are suitable to get a proper tuning of the intake system (in particular, a Venturi nozzle is necessary after the restrictor to recover some kinetic energy; furthermore, a large plenum should be placed between the throttle and the engine, in order to damp the pressure and velocity pulses through the restrictor and to provide an open end reflection to the waves traveling along the intake runner). On the other hand, the higher is the volume between the throttle and the engine, the slower is transient response (and the more difficult is injection parameters calibration). The University team has found a very good trade-off between these issues by adopting an unusual configuration for the plenum. Instead of using a single large volume, two Helmholtz resonators are connected to a short intake runner, as visible in figure 3. Even on a single-cylinder naturally aspirated engine, the influence of these resonators on the intake system dynamics is very complex, since the two pipes (intake duct and air scoop) and the two volumes (cylinder and resonators) form a vibrating system, with two degrees of freedom and two resonant frequencies [19].

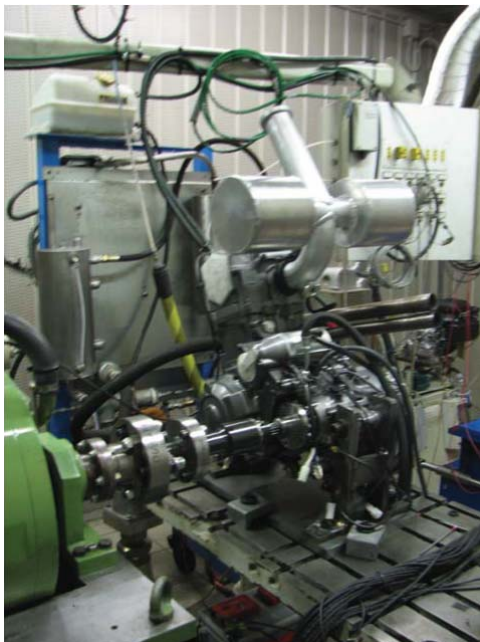


**Figure 3:** View of the Formula engine with the distinctive plenum made up of two Helmholtz resonators.

A first attempt to tune this system may be done by referring to the electrical analog theory, in which capacitors represent volumes and inductors pipes. A sketch of the model is depicted in figure 4. It is observed that in a supercharged and inter-cooled engine, the upstream duct corresponds to the pipe between the compressor outlet and the resonators.

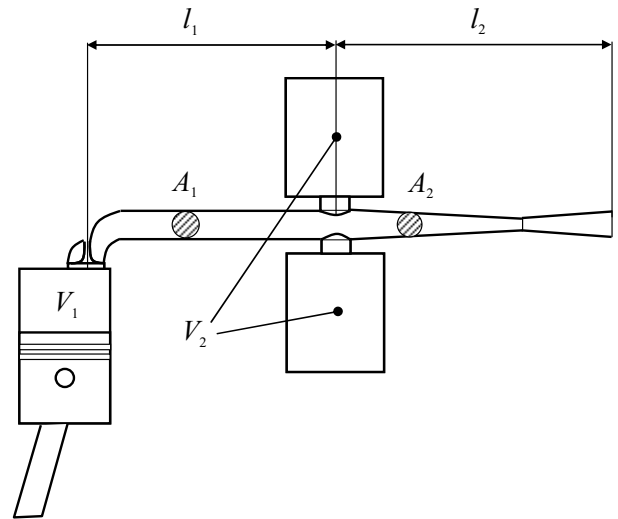


**Figure 4:** Sketch of the Helmholtz resonator model

According to the electrical analog [20], the equation for the calculation of the resonant engine speed is:

$$N_{1,2} = X_{1,2} N_0$$

$$X_{1,2} = \sqrt{\frac{(\alpha\beta + \alpha + 1) \mp \sqrt{(\alpha\beta + \alpha + 1)^2 - 4\alpha\beta}}{2\alpha\beta}} \quad (1)$$

$$N_0 = \frac{c}{2\pi k} \sqrt{\frac{1}{L_1 V_1}}$$

where:

$$\alpha = \frac{l_2 A_1}{l_1 A_2}; \quad \beta = \frac{V_2}{V_1}; \quad L_1 = \frac{l_1}{A_1}; \quad k \cong 2$$

and the average cylinder volume is assessed through:

$$V_1 = V_d \frac{(r_c + 1)}{2(r_c - 1)}$$

where  $V_d$  is the engine displacement and  $r_c$  the compression ratio.

It may be observed that, when adopting a conventional intake system (made up of an inlet runner, a large plenum and an air scoop), the highest engine speed at which the tuning occurs is almost coincident with  $N_0$ , while the lowest speed falls out of the range of interest. Conversely, an intake system with two small Helmholtz resonators yields two tuning peaks, a low and a high engine speed, and presents the further advantage of a