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Development of an engine variable geometry intake system for a Formula SAE application

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Abstract

The Formula SAE is an international competition for vehicle fully designed and built by students from worldwide Universities.
The engine and vehicle design in the Formula SAE competition has to comply with a strict regulation. Regarding the engine intake line an air restrictor of circular cross-section no greater than 20 mm must be fitted between the throttle valve and the engine inlet. The aim of the throat is to limit the engine air flow rate as it strongly influences the volumetric efficiency and then the maximum power.
The present paper is focused on the design of the engine intake system of the Firenze Race Team vehicle in order to optimize its performance in terms of both the maximum power and the drivability of the vehicle.
One of the typical solutions for limiting the air restrictor influence consists of a plenum chamber placed along the intake line downstream of the restrictor. However the plenum involves also a delay in the engine response during the transient phases. The greater is the plenum, the lower are the power losses but the greater is the engine response delay.
Taking advantage of a calibrated 1D model of the engine and a simplified vehicle model, the authors numerically analyzed an innovative solution that is constituted by a variable length duct inside the plenum. When the duct is at the maximum extension, the plenum is excluded from the intake line improving the engine response time. The optimization of the plenum volume and the definition of a preliminary control logic of the innovative system were done in order to obtain the maximum advantages in terms of both performance and engine drivability.

Keywords: Internal combustion engine, variable length duct, plenum, performance, engine response time, optimization

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1. Introduction

The performance of an internal combustion engine depends directly on the amount of air elaborated in every cycle during its functioning. On this basis, a way to limit the maximum power of an engine is to introduce a pressure loss along the intake manifold. According to this principle, Formula SAE rules impose the adoption of a restrictor, with a diameter of 20mm, along the intake line between the throttle valve and the engine inlet. More in detail, the restrictor has the aim to cause a pressure drop that is proportional to the second power of the instantaneous velocity of the airflow.

In order to reduce the influence of the restrictor, it is necessary to minimize the maximum instantaneous flow velocity through it.

A way to obtain the this objective is to place a plenum chamber between the restrictor and the engine. The plenum allows one to minimize the pulsating flow through the restrictor. As a consequence the pressure drop at the restrictor decreases and the mass flow rate elaborated by the engine rises. This allows a growth of the engine performance. The greater is the plenum volume the higher is the power that the engine can provide.

On the other hand, the introduction of a plenum causes a delay in the engine response; more precisely the power requested is supplied with a time delay directly proportional to the plenum volume.

The same issue occurs during decelerations when the brake engine torque helps the car to reduce its velocity.

The restrictor on the intake system affects single-cylinder engines more than multi-cylinder engines, due to their great pulsating mass flow.

To face this issue, the authors studied numerically a variable geometry intake system, for a 4S single-cylinder engine of 498cc for Formula SAE competition. The innovative intake system bypasses the plenum when a high power is not requested and allows one to obtain the best compromise between maximum performance and engine response time.

The effectiveness of the innovative intake system was analyzed numerically with the use of both a commercial 1D code for the analysis of internal combustion engine (Wave®) and a simplified vehicle model (integrated in the 1D code). During the simulations particular attention was put to the analysis of the transient conditions of load and speed.

The performance of the engine obtained whit the new intake solution is compared with the performance of the engine configurations with and without the plenum.

2. Plenum sizing

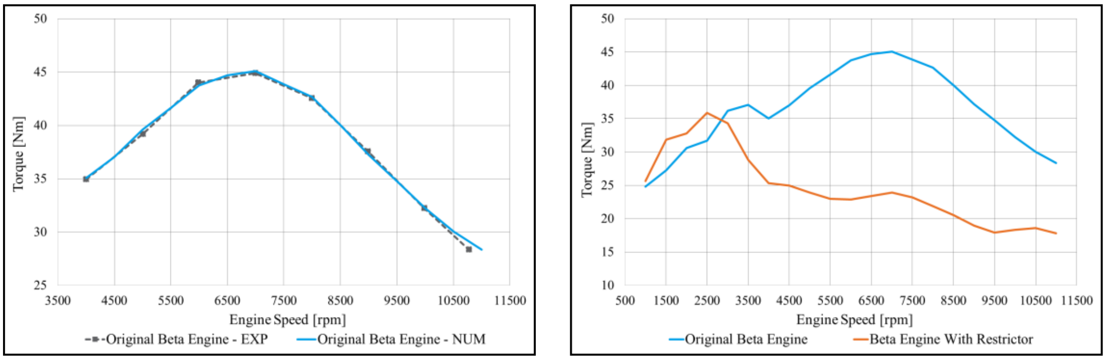
The vehicle of the Florence University for the Formula SAE competition is equipped with a Spark Ignition (SI). engine 4S single-cylinder 498cc supplied by Betamotor (Table 1) [1].

Table 1. Betamotor 498cc engine characteristics.

N° of Cylinders	Strokes for cycle	Engine Type	Bore [mm]	Stroke [mm]	Compression Ratio
1	4	SI	100	63.4	12

The first step to design and optimize the engine for the Formula SAE competition was the calibration of the 1D numerical model in the original engine configuration. The calibration process was based on several experimental data (i.e. torque, in-cylinder pressures, S-curve, gas temperature, etc.) carried out at the engine test bench and was performed following the typical approaches present in literature [2-4]. The results highlighted the good predictability of the numerical model. For brevity of discussion only the comparison between the numerical and experimental torque curves in the full load condition are shown (Figure 1 (a)).

By taking advantage of the calibrated model, the first numerical analysis was focused on the influence of the 20mm restrictor on the engine performance [5]. In Figure 1 (b) the torque of the original Betamotor engine is compared with that of the same engine equipped with the restrictor at full load condition. The restrictor causes a great pressure drop and a power loss that is unacceptable for a racing car.



(a) (b)

Fig. 1. (a) Torque at full load condition of the original Betamotor engine: comparison between the experimental data and the numerical one. (b) Engine torque at full load condition: numerical comparison between the Betamotor engine in the original configuration and the one provided with the restrictor.

In order to limit the negative influence of the restrictor and to reach high values of power, the author designed and optimized a plenum to be placed between the restrictor and the engine (Figure 2).

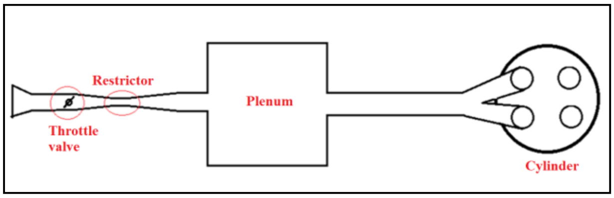


Fig. 2. Scheme of the intake line provided with the plenum.

In order to identify the right sizing of the plenum [6, 7], the authors have considered the engine performance in the full load condition. The plenum volume was numerically changed from 1 to 10 l with a step equal to 1 l. In Figure 3 some significant torque curves among the simulated configurations are shown together with those of the original engine and that with the restrictor but without the plenum. As expected, for the engine configurations obtained with both the restrictor and the plenum, the bigger is the plenum volume the higher is the engine torque [8]. On the other hand, the limited increase of the performance for volumes greater than 5 l does not justify the loss of space inside the car.

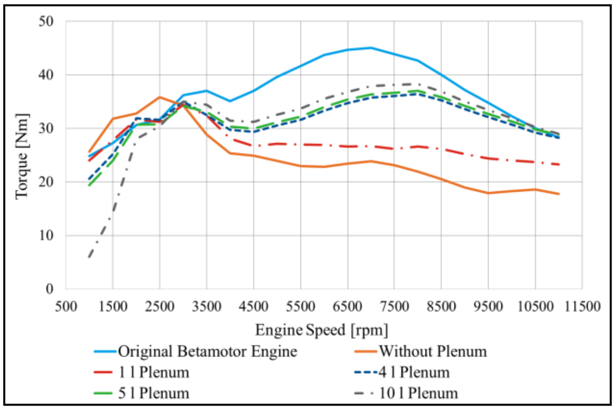


Fig. 3. Engine torque at full load condition: the original Betamotor engine and the configuration with only the restrictor ("Without Plenum") are numerically compared with the engine configurations provided with both the restrictor and different plenum volumes.

The other relevant aspect that needs to be investigated for the correct sizing of the plenum is the response time of the engine. To analyze it, the authors performed numerical transient analyses [9] by considering different size of the plenum.

The simulations were performed by imposing the opening profile of the throttle valve shown in Figure 4. The throttle valve starts to open after 0.5 s and it opens completely from 0 to 90 deg in 5 ms; then the throttle stays fully open for 2 s and finally it closes again. The opening time of the throttle valve is measured on the Firenze Race team vehicle by the telemetry system. The engine speed is imposed constant at 4500 rpm during the whole simulation; this is the engine speed nearest to the clutch-engagement speed that allows to get the Wide Open Throttle (WOT) condition.

The parameter taken into account to estimate the engine response time was the time needed by each engine to reach the 50% of the maximum torque supplied by the engine without the plenum at 4500 rpm.

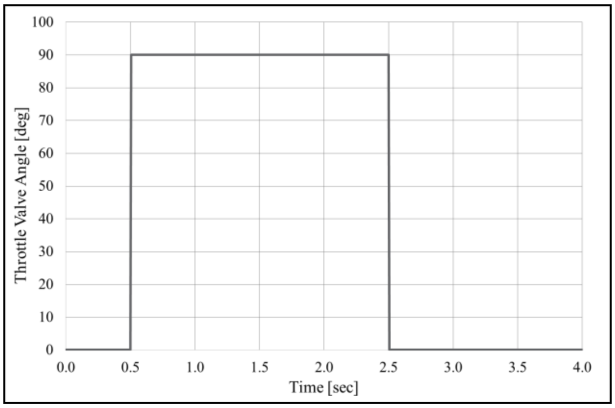
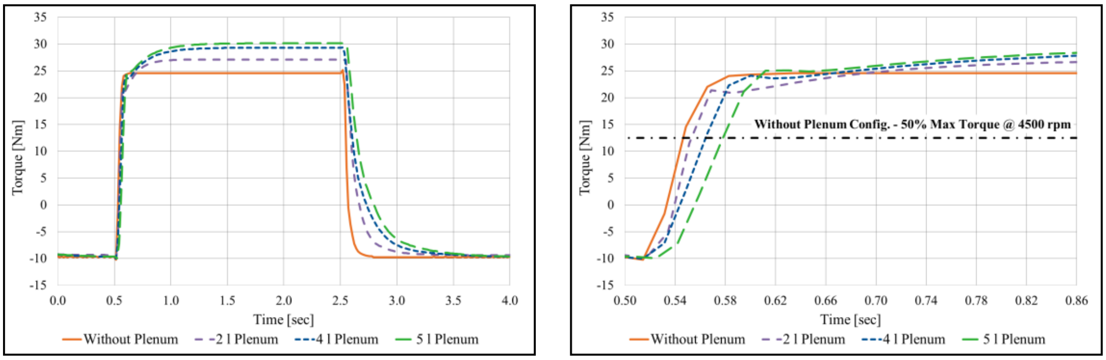


Fig. 4. Opening profile of the throttle valve imposed for the transient simulations of the engine.

In Figure 5 (a) and (b) the trends of the torque supplied by the engine without the plenum and with a plenum volume respectively of 2, 4 and 5 l are depicted. The graph shows that the larger is the plenum volume the greater is the time needed to reach the above-defined value of the torque. Moreover, when the throttle valve closes completely, by increasing the volume of the plenum the time to reach the load condition of full closed throttle increases too (Figure 5 (a)).



(a) (b)

Fig. 5. (a) Engine torque trend during the transient numerical analysis: comparison among configurations with the plenum and without the plenum. The simulations are performed by imposing the throttle opening from 0 to 90 deg at constant engine speed (4500 rpm). (b) Details of the acceleration phase. The dot-dash black line represents the 50% of the maximum torque supplied by the engine configuration without the plenum at 4500 rpm.

From this analysis, it appears that the right design of the plenum is a compromise between the maximum torque (and power) achievable (big volumes) and the minimum response time of the engine (small volumes).

A comparison in terms of power and response time for different engine configurations is shown in Figure 6.

In the authors opinion the 4 l plenum is the best compromise between the maximum torque supplied by the engine and the engine response time. Indeed for plenum volumes higher than 4 l the increase of maximum engine performance is negligible despite of a considerable increase of the time to reach the defined value of torque.

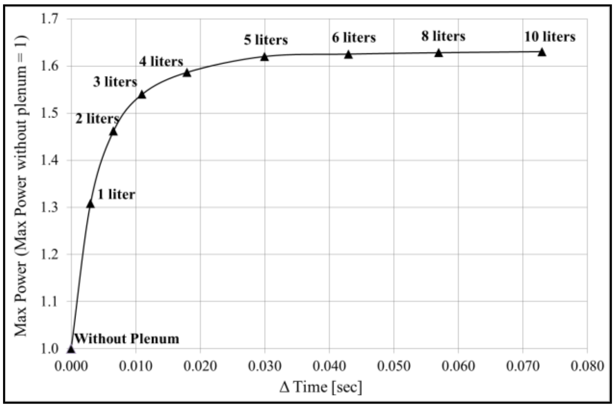


Fig. 6. Numerical comparison among engines equipped with different plenum volumes: in the x-axis is reported the time delay of each configuration to reach the 50% of the maximum torque supplied by the engine configuration without the plenum at 4500 rpm; in the y-axis is reported the maximum engine power of each configuration normalized with respect to the maximum power of the engine without the plenum.

3. Innovative intake system

The previous analyses have highlighted that a plenum of 4 liters allows one to obtain a good compromise between maximum performance and engine response (Figure 6).

Anyway the plenum introduction along the intake line leads to a reduction of both the engine response and deceleration times and could have a strong influence in several tests of the Formula SAE competition (i.e. Acceleration Test, Autocross and Endurance Test).

The best solution to the above-mentioned issue could be that of exploiting the plenum only when high performance is needed and excluding it during transient phases and partial load conditions. More in details, during a quick acceleration, for example from the minimum plate angle to the full load (at constant engine speed equal to 4500 rpm, Figure 4), the torque supplied by the engine without the plenum increases faster than in the engine configuration with the 4 liters plenum as shown in Figure 5 (b). Similarly, during a deceleration the engine torque decreases more slowly with the plenum than without it (Figure 5 (a)) at the expense of a rapid braking of the vehicle.

For years now, variable length ducts have been developed and applied in the racing field with the main aim of tuning the engine in a large speed range [10, 11].

The authors have studied the application of the same mechanical system to exclude the plenum from the engine inlet line when needed. This system would lead to sensitive advantages in terms of engine response without a reduction of maximum power (Figure 7).

In the present paper a preliminary numerical analysis of this innovative system are presented.

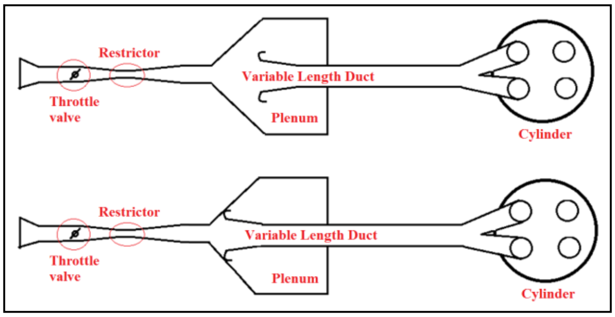


Fig. 7. Sketch of the intake line equipped with the variable geometry intake system when the plenum is included (top of the figure) and when it is excluded (bottom of the figure).

In order to study more accurately the transient phases a simplified vehicle model (integrated in the 1D code) was used. The model couples the engine behavior with the mechanical dynamic characteristics of the vehicle (i.e. mass, transmission, and so on) along an imposed mission profile. In addition, the model also allows the definition of the gear shift strategy, the declutching and the synchronization time of the clutch, and so on.

The effectiveness of the innovative system was studied imposing in the vehicle model different profiles of the throttle valve opening (TVO), as shown in the Figure 8 (a).

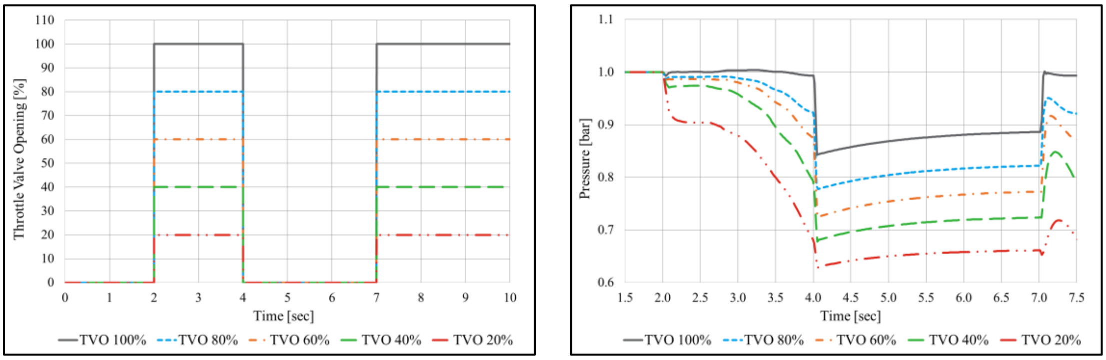
In the first 2 seconds the throttle is at the minimum plate angle and the plenum is excluded by the variable length duct from the intake line of the engine. In all the simulations, the initial conditions along the intake line and inside the plenum, were the standard ambient conditions. After 2 seconds the throttle valve opens to an imposed value.

For each case simulated, the plenum is connected with the intake line only when the throttle valve reaches the imposed maximum value of opening. At the 4^{th} second the throttle valve closes and, as a consequence, the runner duct excludes the plenum. Finally, after 7 seconds there is a second acceleration in which the throttle is opened again at the previous imposed value. The opening/closing time of the throttle was always fixed equal to 5 ms, while the variable length duct opens and closes the plenum with a mechanical delay established to 50 ms. The actuation time of the proposed system is consistent with the actuation time of commercial variable length intake systems.

The simulations were performed for different valve opening from the 20% of the maximum opening to the WOT condition.

At the beginning, with the valve at the minimum plate angle, the plenum is excluded and its internal pressure is the constant ambient pressure (Figure 8 (b)). When the plenum opens, the lower is the throttle valve opening the faster is the decrease of the pressure inside the plenum. When the valve closes to the minimum plate angle and the plenum is still open due to the mechanical delay, the engine draws air basically from the plenum only; as a consequence, the pressure inside the volume falls down sharply (almost at the 4^{th} second of the simulation). When the plenum is closed by the variable length duct, the internal pressure remains constant; a small increment of the pressure inside the plenum is due to the heat transfer between the walls (warmer) and the still air inside.

The lower is the pressure in the plenum when it closes the slower is the second acceleration of the engine. This suggests to open the plenum only for medium – high loads and to close it at low load in order to avoid its excessive emptying and then a considerable delay in the subsequent acceleration.



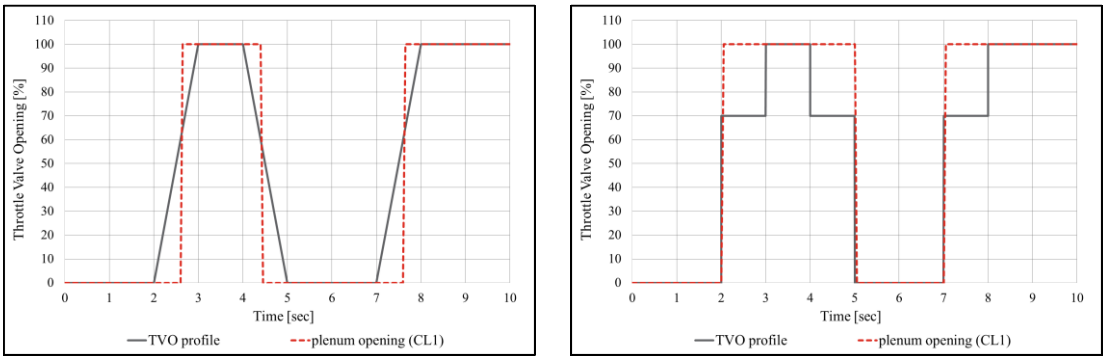
(a) (b)

Fig. 8. (a) Throttle valve opening (TVO) profiles (%) imposed in the engine-vehicle model for transient simulation. (b) Pressure inside the 4 l plenum during transient simulation by imposing different opening profiles of the throttle valve. For each simulated case, the plenum is connected with the intake line only when the throttle valve reaches the opening maximum value with a mechanical delay of 50 ms.

The authors have considered about 0.75 bar as the bottom limit of the plenum depression. As a consequence, by looking at (Figure 8 (b)), when the throttle valve is closed below 60%, the variable length duct has to extend and exclude the plenum, avoiding an excessive depression inside it.

In order to highlight the advantages of this first preliminary control logic (CL1), the response time of the engine was evaluated by imposing two other different TVO profiles (Figure 9 (a) and (b), Profile 1 and Profile 2, respectively).

Both the valve profiles are characterized by two openings up to the full load. The second acceleration (that starts at the 7th second) is always the reference in order to evaluate the effectiveness of the system, because the first one (between the 2th and the 5th second) is used to set the right initial conditions of the whole engine system. Therefore, the analysis will be focused mainly on the second acceleration.



(a) – Profile 1 (b) – Profile 2

Fig. 9. Throttle valve opening imposed in the engine-vehicle model for transient simulation and plenum opening/closing obtained according with the control logic CL1.(a) Profile 1, (b) Profile 2.

The two imposed TVO profiles were simulated with four different intake systems:

- Intake line without the plenum;
- Intake line with the plenum always open;

- Intake line with the plenum open only when WOT condition is reached;
- Intake line with the plenum open only when the TVO overcomes the 60% (CL1).

Considering the Profile 1, Figure 10 shows that the engine configuration with the plenum always open is characterized by the strongest pressure drop inside the volume and consequently in the intake manifold, due to the first deceleration between the 4th and the 5th second. The depression causes the response delay of the engine during the second acceleration. Conversely, the innovative intake system prevents excessive depressions inside the plenum and in the intake manifold.

The CL1 allows both the fastest increase of the suction pressure (Figure 10) and the fastest increase of the supplied power (Figure 11 (a)) that reaches the maximum value more rapidly than in the other cases.

The CL1 is effective in terms of both responsiveness and maximum power:

- In acceleration (Figure 11 (a)), the increment of the engine power is as rapid as in the case of the engine without the plenum; indeed the pressure inside the plenum at the opening moment (TVO reaches the 60%) is high enough to guarantee the best response time, also in comparison with the engine configuration with the plenum open only when WOT condition is reached;
- The advantages in deceleration (Figure 11 (b)) are the most noticeable in comparison to the configuration with the plenum always open; the load condition of full closed throttle is reached very quickly;
- The high power level is assured thanks to the beneficial effect of the plenum volume.

The sudden variations of pressure and power (e.g. between 7.8 and 8.2 seconds of Figure 10 and Figure 11 (a)) are due to the gear shifts.

The same benefits are found with the second imposed mission profile (Figure 12 and 13).

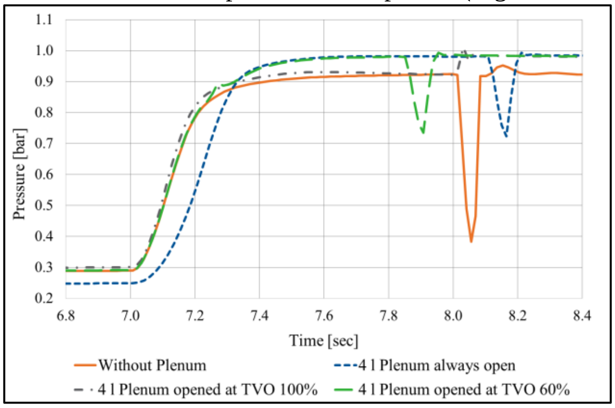
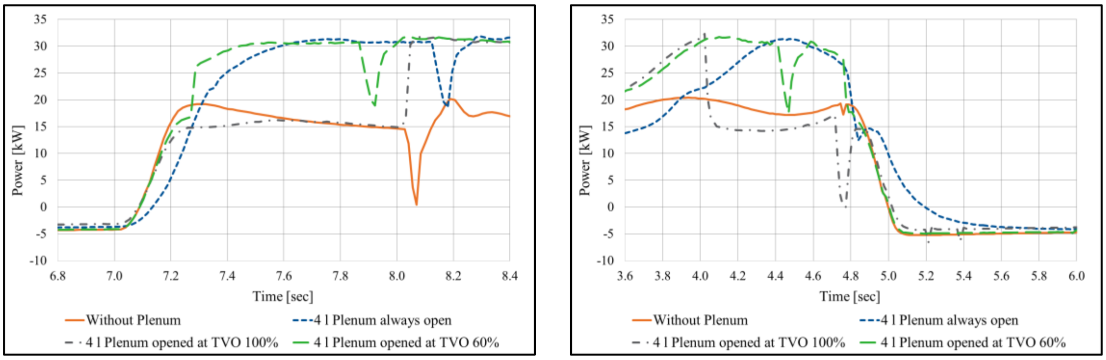


Fig. 10. Intake manifold pressure during transient numerical analysis, detail of the second acceleration of the Profile 1: comparison among engines equipped with different intake systems (without the plenum, with the plenum always open, with the plenum open only when WOT condition is reached and with the plenum open only when 60% of the maximum TVO is reached).



(a) (b)

Fig. 11. Engine power during transient numerical analysis. Comparison among engines equipped with different intake systems (without the plenum, with the plenum always open, with the plenum open only when WOT condition is reached and with the plenum open only when 60% of the maximum TVO is reached).
(a) Detail of the second acceleration of the Profile 1. (b) Detail of the first deceleration of the Profile 1.

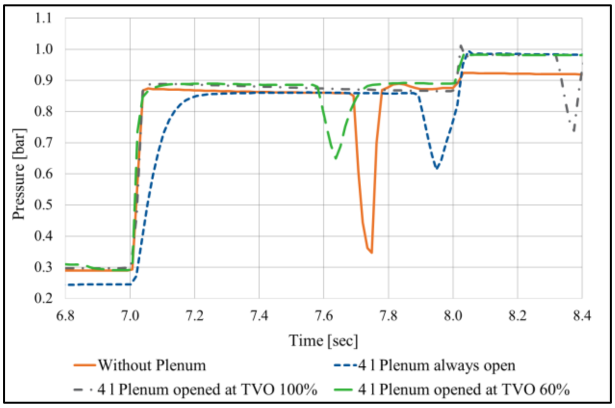
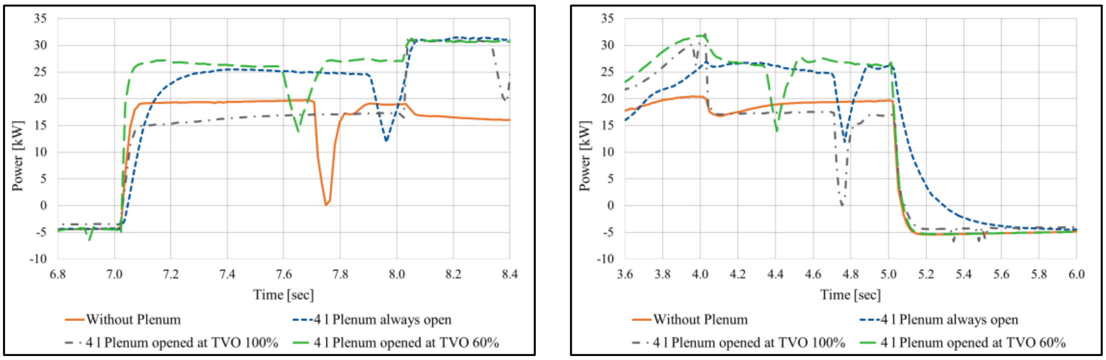


Fig. 12. Intake manifold pressure during transient numerical analysis, detail of the second acceleration of the Profile 2: comparison among engines equipped with different intake systems (without the plenum, with the plenum always open, with the plenum open only when WOT condition is reached and with the plenum open only when 60% of the maximum TVO is reached).



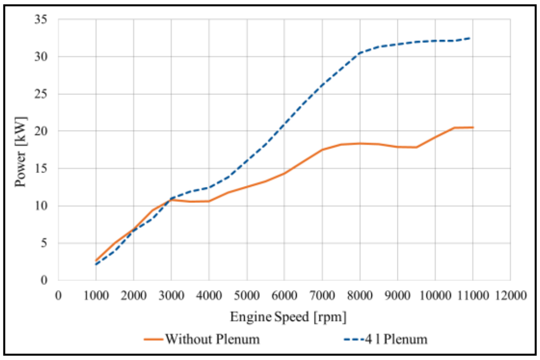
(a) (b)

Fig. 13. Engine power during transient numerical analysis. Comparison among engines equipped with different intake systems (without the plenum, with the plenum always open, with the plenum opened only when WOT condition is reached and with the plenum opened only when 60% of the maximum TVO is reached).
(a) Detail of the second acceleration of the Profile 2. (b) Detail of the first deceleration of the Profile 2.

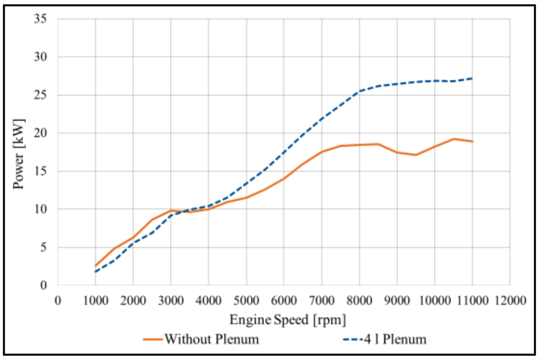
The throttle valve opening is not the only control parameter considered for the intake system. Also the engine speed influences the inlet mass flow. Consequently, it is worth evaluating whether an rpm range does exist in which the variable length duct should bypass the plenum regardless of the load.

Taking into account that a rapid engine response during transients is obtained by excluding the plenum below 60% of the TVO, the authors have considered the stationary conditions of the engine for throttle valve openings over the 60%. The engine configurations without the plenum and with the plenum always open are considered.

The Figure 14 (a) and (b) highlight that, in these stationary conditions, the plenum has to be bypassed by the runner duct in the rpm range where the engine torque obtained without the plenum is higher than that obtained with the plenum.



(a)



(b)

Fig. 14. Engine power at full load (a) and at 60% of the throttle valve opening (b): numerical comparison between the engine with the 4 l plenum and without it.

By cross-referencing the results of the simulations in stationary conditions with the results of the transient simulations, it is possible to draw the second control logic map (CL2) as a function of the throttle valve opening and the engine speed (Figure 15 (a)).

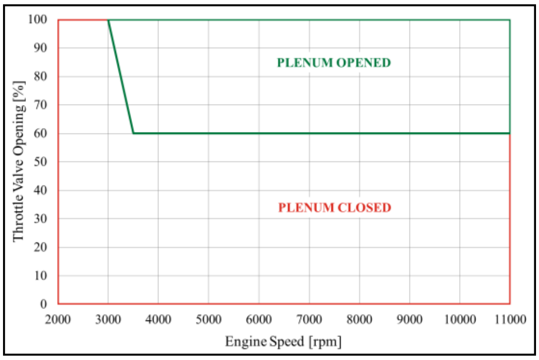
Finally, taking advantage of the dynamic engine-vehicle model [12], the Acceleration Test of the Formula SAE competition was simulated (Figure 15 (b)). During the Acceleration Test, the vehicle must accelerate for 75 meters along a straight path on a level road.

The following engine configurations are compared:

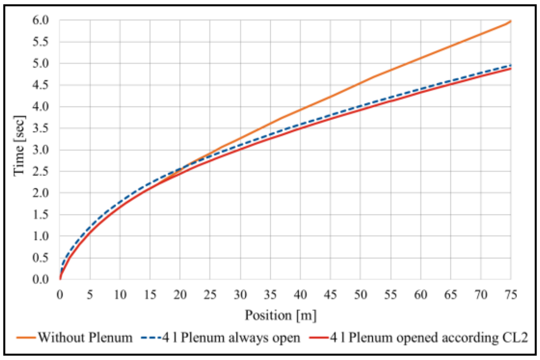
- Engine with the innovative intake system managed according to the CL2 control logic (Figure 15 (a));
- Engine with the with the 4 l plenum always open;
- Engine without the plenum.

The vehicle equipped with the new intake system is characterized by the best starting phase as rapid as the case of an engine without the plenum. The time advantage (0.1 sec) in comparison to the configuration with the plenum always open is maintained during the rest of the Acceleration Test because the two systems, after the starting phase, supply the same maximum power.

The benefits obtained with the innovative intake system should be greater in the other Formula SAE tests (i.e. Autocross and Endurance Test) in which there are more phases of acceleration and deceleration.



(a)



(b)

Fig. 15. (a) Preliminary control logic map (CL2) of the plenum opening/closing.
(b) Numerical simulation of the Formula SAE Acceleration Test performed with the engine-vehicle model: comparison between the vehicle equipped with the engine configuration with the 4 l plenum always open and the vehicle provided with the variable geometry intake system with control logic CL2.

4. Conclusions

The Formula SAE rules impose the introduction of a restrictor of 20mm diameter along the intake line downstream the throttle valve in order to limit the maximum power supplied by the gasoline 4S engine.

One of the most widespread design systems to limit the restrictor influence is the insertion of a properly sized volume before the engine inlet. The plenum allows one to reduce the pressure drop at the restrictor. Consequently, the engine mass flow rises allowing a growth of the engine performance.

The main issue of the plenum introduction, which behaves as a capacity, is the increase of the engine response time during transients.

In the present work the authors have firstly optimized the plenum volume in order to limit the influence of the restrictor and, as a consequence, to improve the maximum performance of the engine. Then in order to improve the engine response time during the accelerations and decelerations of the vehicle, an innovative intake system made up of a variable length duct was investigated. A calibrated numerical model that integrates the engine and the vehicle and allows to simulate both stationary and transient conditions was used. The variable length duct bypasses the plenum when the maximum power is not requested. The preliminary control logic of the system is based on both the throttle valve opening and the engine rotating speed.

The simulations in stationary and transient conditions have shown that it is suitable to exclude the plenum from the suction line both at low engine speeds and when the throttle valve opening is less than 60%. Conversely, the plenum has to be exploited in order to achieve high power.

By considering the presence of the restrictor, the new intake system is the best compromise between maximum performance and engine response time. The results of the numerical activity show how the variable geometry system does not affect the engine maximum power obtained with a properly sized plenum and, at the same time, allows one to gain considerable improvement in terms of acceleration and deceleration of the vehicle.

The advantage of the innovative intake system was also verified by simulating the Acceleration Test of the Formula SAE competition. The benefits should be greater in the other competition tests since these are characterized by more accelerations and decelerations (i.e. Autocross and Endurance Test).

From the above considerations, it is clear the interest in the simulation of the autocross test with a tuned engine-vehicle model based on the real telemetry data. Future developments will be focused on the design of the mechanical apparatus for the actuation of the variable length duct.

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