

The Effects of Intake Plenum Volume on the Performance of a Small Normally Aspirated Restricted Engine

L. J. Hamilton and J. E. Lee

US Naval Academy

ABSTRACT

Intake tuning is a widely recognized method for optimizing the performance of a naturally aspirated engine for motorsports applications. Wave resonance and Helmholtz theories are useful for predicting the impact of intake runner length on engine performance. However, there is very little information in the literature regarding the effects of intake plenum volume. The goal of this study was to determine the effects of intake plenum volume on engine performance for a restricted naturally aspirated engine for Formula SAE (FSAE) vehicle use. Testing was conducted on a four cylinder 600 cc motorcycle engine fitted with a 20 mm restrictor in compliance with FSAE competition rules. Plenum sizes were varied from 2 to 10 times engine displacement (1.2 to 6.0 L) and engine speeds were varied from 3,000 to 12,500 RPM. Performance metrics including volumetric efficiency, torque and power were recorded at steady state conditions. Experimental results showed that engine performance increased modestly as plenum volume was increased from 2 to 8 times engine displacement. Increasing plenum volume beyond 8 times engine displacement resulted in significant improvement in performance parameters. Overall, peak HP was shown to increase from 54 kW to 63 kW over the range of plenums tested. While it was clear that larger intake plenums yielded better steady state performance, their effect on transient performance was not explored and will be the subject of further research.

INTRODUCTION

Intake system tuning is a well known and cost effective method of increasing the performance of internal combustion engines without the use of mechanical turbochargers or superchargers for motorsports applications. In general, intake systems consist of an airbox or plenum chamber (fed by a throttle body) and runners that lead from the plenum to each cylinder. Engine designers strive to take advantage of pressure wave dynamics in the intake system to increase the

mass of air transferred to the combustion chamber over desired RPM ranges.

While the actual wave dynamics are complex for a multi-cylinder engine, the intake system can be modeled as a simple Helmholtz resonator [1]. When the intake valve opens and the piston descends, a rarefaction or expansion wave travels upstream in the runner toward the plenum. Upon reaching the runner opening in the plenum, this wave is partially transmitted (still as an expansion wave) into the plenum. At the same time, part of the original expansion wave is reflected as a compression wave that heads back to the cylinder. If the compression wave arrives at the intake valve before it closes, the increased pressure will effectively force more air into the cylinder [2]. This tuning effect or resonant supercharging leads to increased volumetric efficiency and torque. Meanwhile, the expansion waves will travel to the inactive branches (with closed valves) and be reflected as expansion waves back to the active runner. These expansion waves reduce intake runner pressure and have the effect of reducing volumetric efficiency [1]. Typically, intake tuners focus on runner geometry (length and/or cross section area) and plenum size and shape. An excellent overview of resonant supercharging is provided by Benajes et al [3].

This method is particularly useful for vehicles competing in the Formula SAE (FSAE) design series where the extra weight and complexity of mechanical boost systems could be detrimental to overall performance. The FSAE series provides college students from around the world to conceive, design, fabricate and compete a small scale formula style vehicle based on a comprehensive set of design constraints. Several of the constraints pertain to engine and intake design. For example, engine size is limited to 610cc and all intake air must pass through a restrictor of circular cross section (20 mm for gasoline or 19 mm for E85) [4].

Some excellent studies have been published to document the effects of intake tuning on a restricted engine suitable for use in the FSAE design series. Jawad et al evaluated four different intake designs with a Honda™ CBR600 F4i engine coupled to a water brake

dynamometer [5]. Their performance criteria were based on total area under the power curve for each configuration. They focused primarily on novel runner geometry approaches and did not document changes in plenum volume.

McKee et al provided a superb contribution to optimization of this class of engines by experimentally evaluating the effects of diffuser length (after the restrictor), runner length, camshaft modifications and exhaust tuning [6]. However, they selected a plenum volume of 3.5L and did not vary it during testing. This decision was based on model predictions which did not show much benefit by increasing plenum volume beyond this amount.

The effect of plenum volume on engine performance was studied and reported by Ceviz [7] as a basis for variable intake plenum technology. He installed plenum additions (90 and 180 cc) to the original intake manifold of a 1.6L four cylinder gasoline engine over a modest RPM range of 1250 – 3000 RPM. While he found that increasing plenum volume increased power at the mid-RPM range, plenum size had to be reduced for best performance at higher speeds. It should be noted that this engine was equipped with a carburetor and the author cited difficulty with proper AFR control when changing plenum size.

The objective of the current study is to determine the effects of plenum size on volumetric efficiency, torque and power for a restricted intake 600cc motorcycle engine for use in Formula SAE applications under steady state operating conditions.

EXPERIMENTAL SETUP

EXPERIMENTAL APPARATUS

All testing was conducted using a 2002 Honda™ CBR600 F4i engine equipped with a Microsquirt™ engine control unit (ECU). The engine characteristics are listed in Table 1. Engine performance parameters were measured using a Land and Sea™ water brake dynamometer coupled to the output shaft. The dynamometer was equipped with a load servo to maintain a specified RPM regardless of throttle position. The intake apparatus included a throttle body, an intake pipe with a circular 20 mm diameter restrictor, a custom variable volume intake plenum and four 5 cm aluminum intake runners as shown in Figure 1. A 0 – 2 bar Kistler™ piezoelectric pressure transducer was mounted in the plenum adjacent to the runner leading to cylinder #1 with a data rate of 40 kHz. An ECM™ 1200 oxygen sensor was mounted in the exhaust header approximately 12 cm from exhaust valve to provide positive feedback to the ECU to maintain proper AFR control. The AFR target in the ECU was set to stoichiometric for all test points. Injector sequencing was selected to minimize pressure fluctuations in the fuel rail.

The intake plenum was designed as a simple aluminum box with a movable ceiling to provide 10 discrete volumes for testing. The possible volumes were based on engine displacement and ranged from 1 (0.6L) to 10 (6.0L). In all cases, the entrance to the plenum via the restrictor was not changed; only the ceiling was raised or lowered to change plenum volume. The plenum can be seen in Figure 1.

Table 1: 2002 Honda F4i Engine Specifications

Engine configuration	Inline four, 4 stroke, DOHC
Displacement	600 cc
Fuel system	EFI
Cooling system	Water
Lubrication system	Wet sump
Compression ratio	12:1
Valves per cylinder	4
Bore	67.0 mm
Stroke	42.5 mm
Valve timing	
IVO	30° BTC
IVC	60° ABC
EVO	50° BBC
EVC	10° ATC

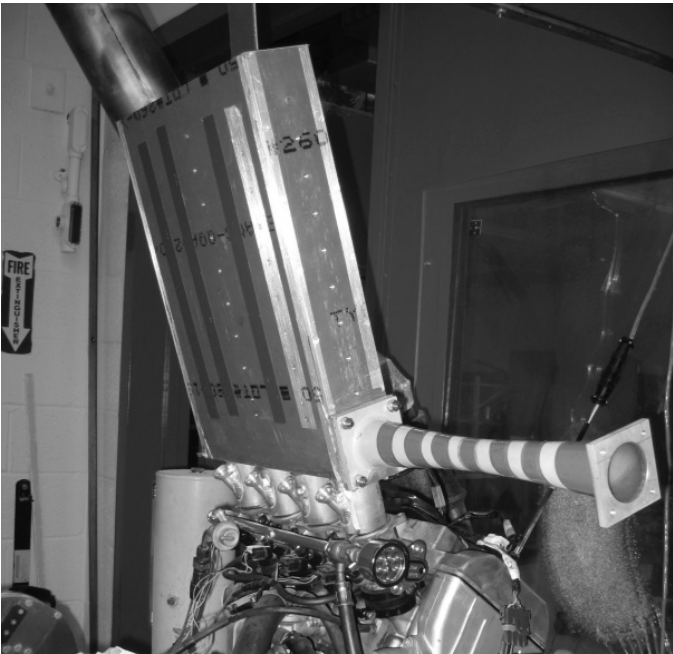


Figure 1: Intake system

Volumetric efficiency, a measure of an engine's air breathing capacity, was one of the desired parameters to be evaluated in this study as it directly relates to torque produced by an engine [8]. It is determined by dividing the actual mass of air consumed by the ideal air mass that could be drawn in based on displacement volume as shown in equation (1).

$$\eta_v = \frac{\dot{m}_{air,actual}}{\dot{m}_{air,ideal}} \quad (1)$$

where

$$\dot{m}_{air,ideal} = \frac{P_{atm} V_{disp}}{RT_{air}} \left(\frac{RPM}{2} \right) \quad (2)$$

Since the engine was not equipped with a mass airflow sensor, fuel flow rate and AFR were used to determine actual air flow through the engine using equation (3).

$$\dot{m}_{air,actual} = AFR \dot{m}_{fuel} \quad (3)$$

A fuel injector calibration test was performed to determine actual fuel flow for a given pulse width. For this calibration, the fuel rail was pressurized to 4.0 bar and a single injector was activated for 1000 'shots' into a graduated cylinder to get an accurate volumetric fuel flow rate for various pulse width values. The result of this calibration is shown in Figure 2. Notice that the curve intercepts the x-axis at 1.1 ms which represents the opening time for these injectors. Using this calibration relationship yields the following equation for fuel mass flow rate:

$$\dot{m}_{fuel} = \rho_{fuel} (0.0036PW - 0.0039) \left(\frac{RPM}{2} \right) \quad (4)$$

where PW is the fuel pulse width in msec.

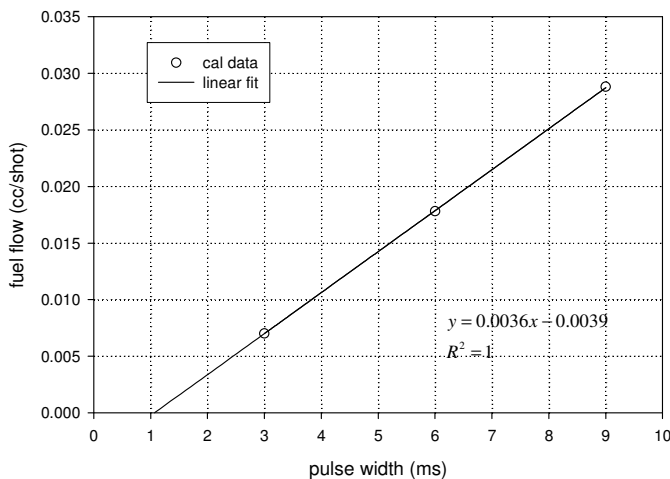


Figure 2: Injector calibration at fuel pressure = 4.0 bar

For all testing, spark timing was set according to the curve shown in Figure 3. This curve represents experimentally derived maximum brake torque spark timing for the range of 1300 to 12,500 RPM. Engine knock was not encountered on any of the test runs.

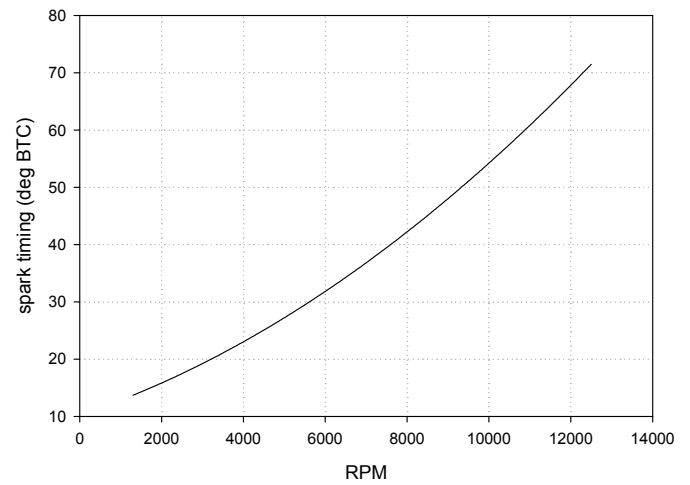


Figure 3: Spark timing curve

EXPERIMENTAL PROCEDURES

All testing was performed in a climate controlled test cell with the engine fully warmed up. Prior to each test period, test cell temperature and barometric pressure were recorded. Standard SAE correction factors were used for all performance results. Plenum volumes were varied from 1.2 L to 6.0 L in 0.6L increments. Special care was taken to ensure that all seams and access holes were sealed prior to testing. For each volume, the engine was stabilized at WOT from 3000 to 12,500 RPM at 500 RPM intervals using the RPM-hold feature of the dynamometer. Absorber torque, fuel pulse width and AFR were recorded for each test point. Premium gasoline with a (R+M)/2 octane rating of 94 was used for all test points.

RESULTS AND DISCUSSION

FULL RPM SWEEP

Figure 4 and Figure 5 show graphical representations of the effects of plenum size on torque at various engine speeds. At low RPM, the smaller plenum appears to produce higher torque than the large plenum although the effect is modest. However, above 7,000 RPM, it is clear that torque tends to increase significantly as plenum size increases. This effect is more pronounced at higher RPM. In fact at the maximum RPM tested, torque dropped from 48 Nm to 36 Nm when comparing the largest and smallest plenums; a 25% loss in torque.

It is also evident that there are two distinct torque peaks; one at approximately 6500 RPM and the second near 10,000 RPM. It is also interesting to note that the torque peak has a very weak dependence on plenum size. For the 6.0 L plenum, torque peaks at 54.5 Nm at 10,000 RPM while the 1.2 L plenum results in a peak of 48.5 Nm at 9500 RPM. This is because runner length is the primary factor in determining the frequency (driven by engine RPM) for resonant supercharging [3]. Later in this paper, the effects of plenum size on engine performance operating at 9500 RPM will be more closely examined.