COBEM-2017-1693
THE EFFECTS OF VARIABLE-LENGTH INTAKE MANIFOLD ON ENGINE PERFORMANCE: LITERATURE REVIEW AND NUMERCAL STUDY ON HCCI ENGINE

João Vitor Alves
Leonel Rincon Cancino
Internal Combustion Engines Laboratory - LABMCI - Automotive Engineering - CTJ
Federal University of Santa Catarina, Joinville, SC, Brazil
j_ alves@outlook.com
l.r.cancino@ufsc.br

Abstract. *The current work present a literature review about the development of variable length presenting the theoretical basis of its operation, as well as its possible advantages and applicability used by several engine developers as well as its effects on the engine performance. Through a literature review is sought to study and analyze the physical behaviors of a variable length intake manifold system and also the advantages of using this method, a supporting material that summarizes the literature will help guide the development of future projects. In order to check the influence of variable-intake length in HCCI engines, a numerical simulation was performed. A six cylinder engine, 6126.11* cm^3*, compression ratio of 18 covering an engine speed range of 2000 rpm to 3000 rpm, using five intake lengths from 448 mm to 1093.75 mm was simulated in AVL BOOST*^{TM}*. A skeletal model for n-heptane was used in order to represent the in-cylinder combustion process. Numerical predictions show the influence of variable intake length in the engine performance, returning different values in the volumetric influence, specific fuel consumption, power, torque, peak firing temperature and combustion star angle before the top dead center.*

Keywords: *Variable-length intake manifolds, Engine performance, Optimization, AVL-Software, HCCI engine.*

1. INTRODUCTION

In the search for more efficient cars, researchers look forward to find ways to increase the power of small engines, boosting the intake is one of the most common procedures. Frequently the length of intake manifolds is designed to meet the needs of only a certain interval of engine speed, which differs depending on its purpose of use. Of this form, fixed geometry collectors are commonly used to seek the optimization of intake for a specific range of engine speed, usually near the peak of the motor torque curve, where the air pulsating mass effects increases the engine volumetric efficiency, although this measure sacrifices the performance in other rotation ranges. Seeking a way to improve the engine admission systems, the variable geometry admission method emerges as an alternative to increase the volumetric efficiency when compared to turbochargers possible solution, modifying its length to meet the needs of the engine. The intake system of a car is the responsible for conducting atmospheric air to the intake valves inside the engine. The intake system consists of air filter, intake tube, plenum and runners. The engine's behavior is directly affected by the amount and manner in which air is displaced throughout the system until it is admitted to the combustion chamber, the whole course is influenced mainly by the geometric dimensions of the assembly, which may increase or decrease the volumetric efficiency of the engine. Volumetric efficiency is used as an overall measure of the effectiveness of a four stroke cycle engine and its intake and exhaust systems as a pair pumping devices (HEYWOOD, 2000). The performance of an internal combustion engine is strongly associated with the amount of air that is admitted and retained in cylinders' interior, because as more air is admitted, larger will be the amount of fuel that will be added and posteriorly oxidized (BRUNETTI, 2013). The intermittent or pulsating nature of the airflow through the intake manifold into each cylinder may develop resonances in the airflow at certain speeds. These may increase the engine performance characteristics at certain engine speeds, but may reduce at other speeds, depending on manifold dimensions and shape. Conventional intake manifolds for vehicles have fixed air flow geometry and static intake manifold. With a static intake manifold, the speed at which intake tuning occurs is fixed. A static intake manifold can only be optimized for one specific number of revolutions per minute (rpm), so it is beneficial to develop a method to vary the intake length/volume, since the engine operates over a broad speed range. Variable length intake manifold technology uses the pressure variations generated by the pulsating flow due to the periodic piston and valve motion to produce a charging effect (CEVIZ, 2007). Seeking a solution to improve the current conventional admission systems, the variable geometry runners method appears as solution, modifying its length to achieve the ideal tuning condition, thus increasing the volumetric efficiency. Given the increasing need for more powerful and efficient engines, the variable intake manifold system, currently used in sports cars, appears as a simpler and cheaper alternative for optimizing volumetric efficiency compared to the usual turbochargers applied in passenger vehicle engines.

2. VARIABLE-LENGTH INTAKE MANIFOLD LITERATURE REVIEW

The earliest researchers to realize the potency of the pulsating mass effect was MORSE *et al.* (1938), where stated that when one of the motor frequency (rpm / 120) harmonics equals one of the resonant frequencies of the intake tube, the pressure fluctuations in the valve will be large. If the portion of the cycle when the inlet valve is nearly closing coincides with the time when the pressure is less than the average, the waves will reduce the power output; but if the valve is nearly closing when the pressure is greater than the atmospheric, then the waves will have a boost effect and will result in an increase in power, one of the results of their studies can be seen in Fig. 1(a). PEREIRA (2008), presents very well the excitation generated by the opening and closing of valve in the intake ducts in Fig. 1(b). It can be seen that the closing of the intake valve causes excitation of the inlet gases, resulting in an oscillation in the pressure at the valve door. MORSE *et al.* (1938) already knew the effects of air flow in intake ducts, however, until the mid 1950s engineers used to develop intake manifolds as short as possible, believing that this would increase engine power. The first vehicle to use an intake manifold with an ideal length for the engine was the Mercedes Benz 300SL in 1954 which introduced the technology to the world and changed the way in which intake systems were developed. The movement of an internal combustion engine is cyclical and consequently, will also be the movements of the admitted gases. Because of this oscillatory characteristic, occurs an effect called wave action, as HARRISON (2004) presented through two phenomena, first by acoustic resonances and wave phenomena and second by inertial filler, also called ram effect.

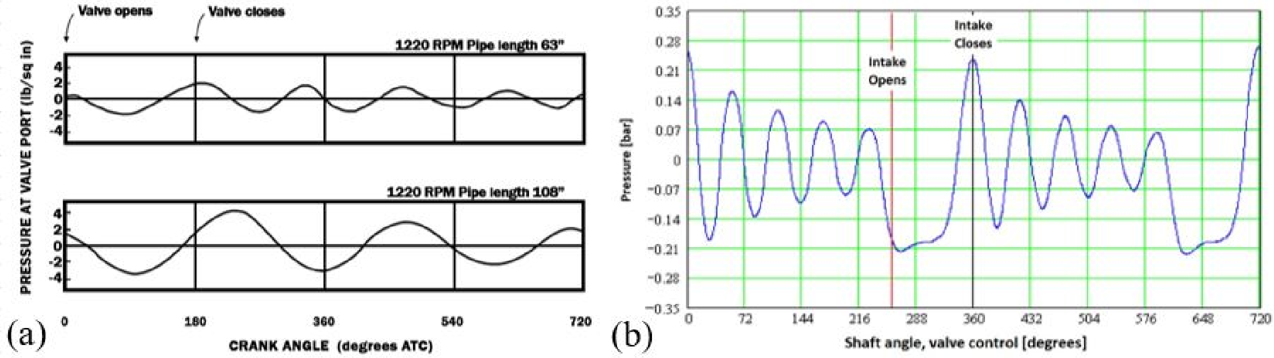


Figure 1. (a) Typical pressure records: constant engine speed, two different intake pipe lengths. Source: (MORSE *et al.*, 1938). (b) Pressure on inlet valve door according to the camshaft angle, Source: (PEREIRA, 2008)

HARRISON (2004) further argue that among wave action phenomena, inertial induction predominates at high velocities, whereas acoustic resonance and wave phenomena were dominant at low rotational speeds. It is important to note that the engine used by HARRISON (2004) considered low revs such as 7000 rpm and high as 1300 rpm because it was an experimental formula 1 engine. The results obtained in the measurements made by HARRISON (2004) for the engine at 7000 rpm and 1300 rpm can be seen in Fig. 2(a) and Fig. 2(b).

The information presented shows that the excitation frequency is directly linked to the engine speed and number of cylinders.

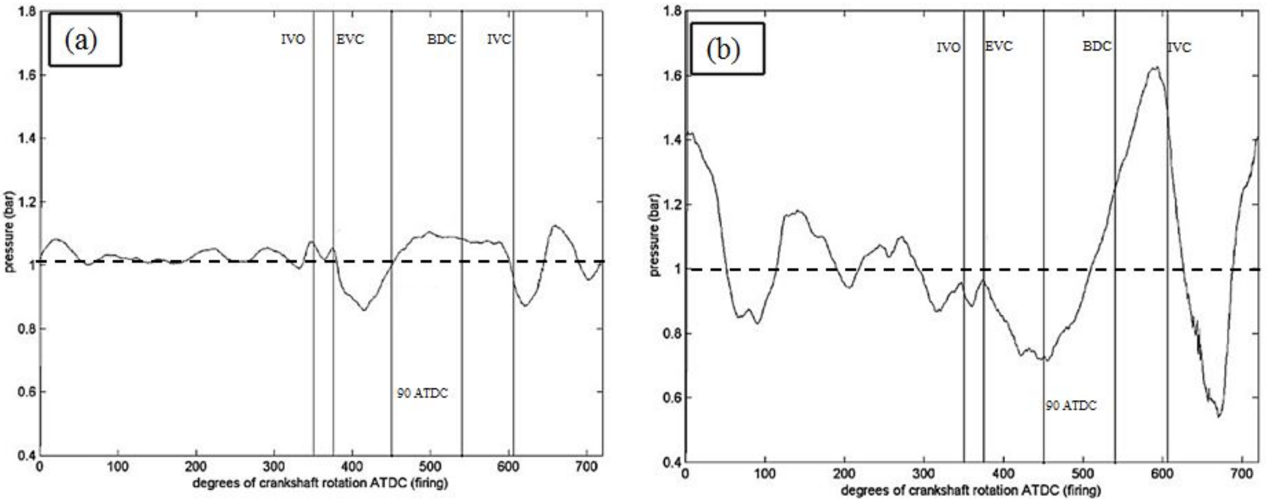
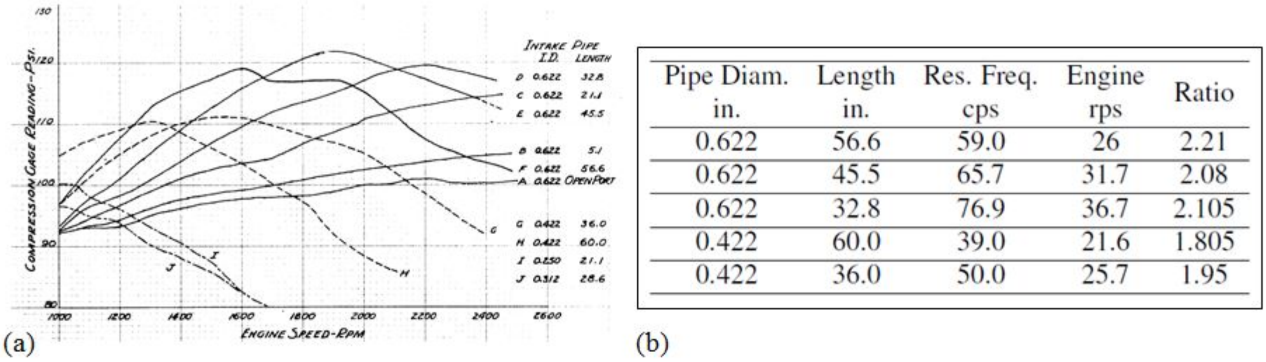


Figure 2. Single cylinder pressure measurement at (a) 7000 rpm and at (b) 1300 rpm, Source: (HARRISON, 2004).

2.1 Helmholtz resonator effect

In the early 50's ENGELMAN (1953) started studying the surge phenomena in engine scavenging, in a doctoral thesis with the same name. In his work ENGELMAN (1953) defined the intake system as a Helmholtz resonator and rewrote the resonance frequency equation of a Helmholtz resonator to cover the characteristics of a two stroke cycle engine, the main difference between the two models is the distinctive cavity and acoustic inductance that a engine cylinder has. ENGELMAN (1953) developed experimental studies, in which it was possible to see, that according to the intake pipe E, for example, is seen in Fig. 3(a) to produce at least 15 per cent more compression than the wide open port over the entire range between about 1450 rpm and 2350 rpm, a range of 1.6 to 1.0. The other pipes showed similar trends. After several practical studies, ENGELMAN (1953) found the ideal length for intake ducts, the table with the results can be seen on Fig. 3(b)



Pipe Diam. in.	Length in.	Res. Freq. cps	Engine rps	Ratio
0.622	56.6	59.0	26	2.21
0.622	45.5	65.7	31.7	2.08
0.622	32.8	76.9	36.7	2.105
0.422	60.0	39.0	21.6	1.805
0.422	36.0	50.0	25.7	1.95

Figure 3. (a) Summary of compression tests with open exhaust. (b) Mean static Helmholtz resonator frequency and engine speed at maximum compression. Source: (ENGELMAN, 1953).

As the Fig. 3(b) shows, the ideal ratio between the resonant frequency of the Helmholtz resonator and the engine speed in revolutions per second (rps) is approximately 2, thus, the frequency obtained by the resonant frequency equation of ENGELMAN (1953), must be two times the speed of the engine. Based on ENGELMAN (1953) ideas, THOMPSON (1968) investigated a four stroke diesel engine and discovered that, although the effects of the resonance become significant when the volume of the inlet system becomes eighty percent of the cylinder volume or more. Based on Engelman's work,THOMPSON (1968) developed an equation to find the speed, in RPM, at which the maximum gain in breathing occurs, to obtain this equation he used not only geometrical inputs of combustion chamber and engine, but also the ratio found by ENGELMAN (1953), seen on Fig. 3, that for most engines the value is something between 2.1 and 2.2.

2.2 Ram charging

The use of the inertia principle of energy conservation to increase the volumetric efficiency of the engine can be called ram charging. The effect is described by HEISLER (1995) as: At the end of the exhaust stroke and the beginning of the induction stroke the inlet valve opens and the piston commences to move away from top dead center (TDC).

The outward accelerating piston quickly expands the space between the cylinder head and piston crown. Instantly,the depression generated in this rapidly enlarging space will be transmitted to the inlet port via the annular passage formed between the valve head and its seat. This drop in pressure immediately causes the column of charge in the induction tract to move as a whole towards the open inlet valve. The large cross-sectional area of the piston relative to that of the much smaller intake tract cross-sectional area plus the acceleration of the piston, forces the column of the charge in the tract to acquire a high flow velocity. The momentum built up by the fast moving column of charge in the intake tract is brought rapidly to a halt when the inlet valve closes against the flow. Thus the kinetic energy generated by the fast-moving column of charge is now converted into pressure energy in the blanked-off inlet port. Consequently, the density of the trapped charge rises. It is this rise in pressure at the port which enables filling of the cylinder to continue after bottom dead center (BDC) and for the induction period to have an early start due to the pressurized charge momentarily stored behind the inlet valve head when it opens. The greater the momentum produced, the greater the rise of pressure, and if energy losses are very low in accelerating the flow, the inertial ram effect will be beneficial in cramming that extra mixture into the cylinder. In the following figures can be seen the relationship between ram charging and inlet tract length and diameter. Fig. 4(a) shows the effect of diameter with fixed length and Fig. 4(b) shows the effect of length with fixed diameter. By analyzing the figures presented by HEISLER (1995), it can be concluded that by keeping the length of the conducts fixed, the larger the diameter, the greater the speed of the motor at which the peak of volumetric efficiency would occur. As MOURA (2014) states, the dimensioning of the inlet ducts is always a compromise between low torque (drivability) and high torque (power).

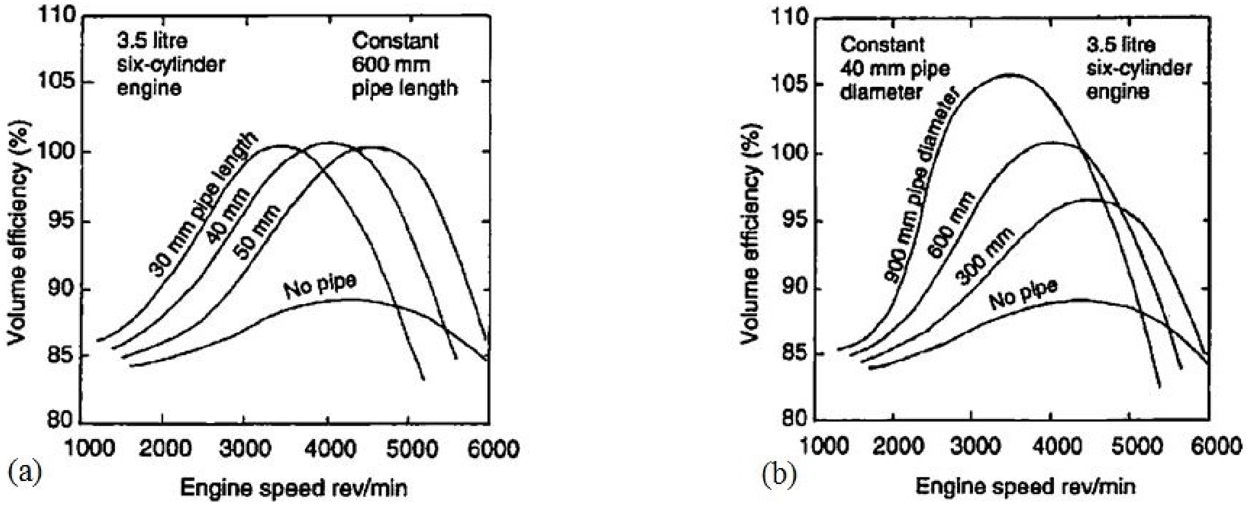


Figure 4. (a) Impact of tract diameter in volumetric efficiency (constant tract length), (b) Impact of tract length in volumetric efficiency (constant tract diameter). Source: (HEISLER, 1995).

Considering Fig.4 (a) and (b), can be concluded that different length of inlets results in different peaks of volumetric efficiency and consequently different peaks of power and torque. In the two images can also be seen, that the most part of the engine speed range can be covered with at least three different inlet tract lengths.

2.3 Application of variable-length inlet tract

POTUL *et al.* (2014) developed a similar study in a simulation for the engine of the motorcycle KTM 200 Duke (spark-ignition, liquid-cooled, Displacement 200 cm^3, Bore 72 mm, Stroke 49 mm, Max. Power 25 bhp and Max. Torque 19.2 Nm) in the software LOTUS SIMULATION TOOLS. Trying to improve the conventional intake system of the engine, the researchers simulate the impact of the length (200 mm, 250 mm and 300 mm) on a variety of performance values, as the torque output (blue line), power output (brown line), brake specific fuel consumption (bsfc)(red line), brake mean effective pressure (bmep)(green line). The results obtained can be seen on Fig.5. According to the researches, their line of interest was the blue one and it was observed that torque peak and torque output characteristics varied significantly with change in length of intake. Also the bmep curve was similar to the respective torque curve. The other variables such as power output and bsfc did not vary much. The working points were imported in a graph plotter and the torque curve for all three lengths were compared on Fig.5(d).

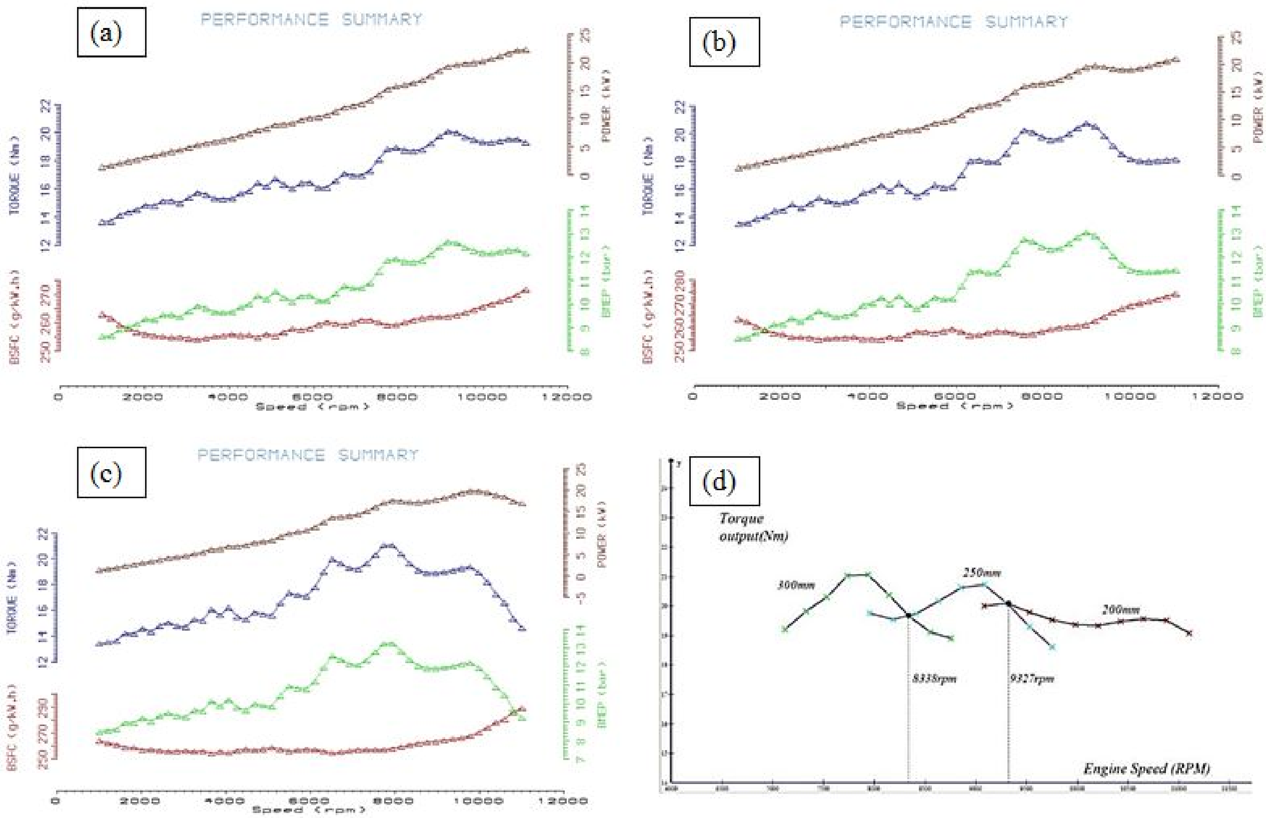


Figure 5. Graph for Plenum Length (a) 200mm, (b) 250mm, (c) 300mm and (d) Comparison of torque output for different lengths 200mm, 250mm and 300mm. Source: (POTUL *et al.*, 2014).

The comparison of torque curve in the three graphs shows the intersection points. These are optimum points at which the length of the manifold should be changed by 50mm length. Now that we have optimum shift point, 8338rpm and 9327rpm we can now proceed to development of a system that could incorporate this idea POTUL *et al.* (2014). Another similar case of engine intake tuning is the work of JAGADISHSINGH and JADHAV (2016), where the simulated engine was an Kirloskar TV1, (Single-cylinder, 4-stroke, spark-ignition, Water-Cooled, Displacement $661cm^3$, Bore 87.56 mm, Stroke 110 mm, Max.power 5.2 kW). JAGADISHSINGH and JADHAV (2016) found the ideal length for each engine speed range using 1D simulation in the Lotus Engine Simulation software. The results Obtained by JAGADISHSINGH and JADHAV (2016) are in Fig. 6(a) and combining the results, (JAGADISHSINGH and JADHAV, 2016) got the best result for volumetric efficiency, as in the Fig. 6(b).

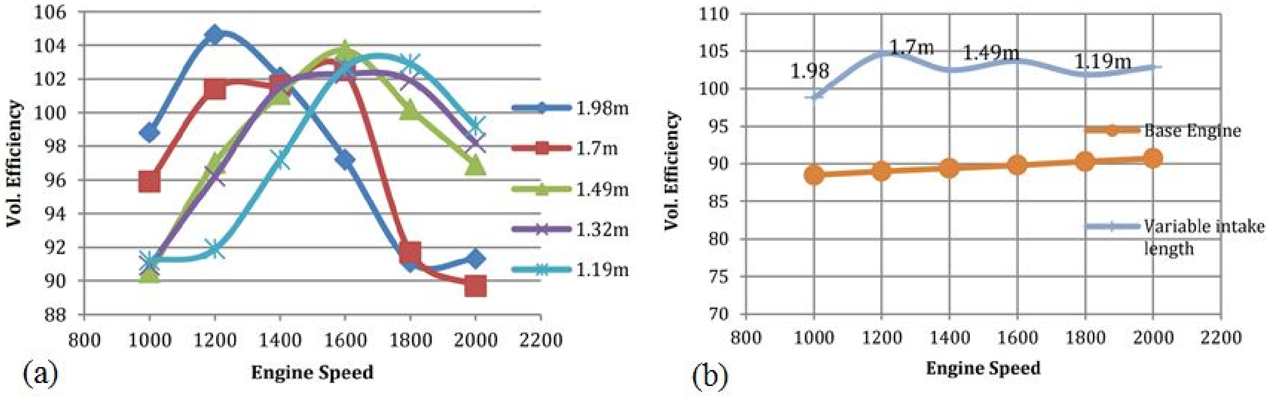


Figure 6. (a) Volumetric efficiency versus engine speeds for varying intake length. (b) Volumetric efficiency Gain by varying intake length (1-D Simulation). Source:(JAGADISHSINGH and JADHAV, 2016).

After the results obtained by simulation, practical tests were carried out to validate these results. The Tab. 1 shows the comparison between simulation and the practical test.

Table 1. Base Engine performance, Source:(JAGADISHSINGH and JADHAV, 2016)

Speed (rpm)	Ideal Intake Length (m)	Volumetric Efficiency (%)			Brake Power (KW)			Brake Torque (Nm)		
		Base stock intake	Simulation stock intake	Experiment custom intake	Simulation stock intake	Simulation stock intake	Experiment custom intake	Base stock intake	Simulation stock intake	Experiment custom intake
1200	1.98	71.3	89	95,5	1.2	3.3	2.0	9.5	26.44	14.4
1400	1.7	82	89.4	87.2	2.0	3.9	4.0	13.7	27.17	26.71
1600	1.49	81	89.8	86.1	4.3	4.5	5.2	27.34	27.17	30
1800	1.19	79.1	90.3	84.6	4.8	5.8	5.6	26.3	27.44	32.5

According to the author, the experimental engine performance as in table above is somewhat lower than that of the simulations results, that is may be because of the reduction in volumetric efficiency as compared to the simulated one. There are a lot of factors contributing to the degradation in engine breathing such as minor leakages in the intake system, curvature and surface roughness of the intake manifold, etc. The Tab. 1 can also be seen the improvement in engine performance due to custom intake length. The compilation of improvements can be seen on the Fig. 7(a) and (b).

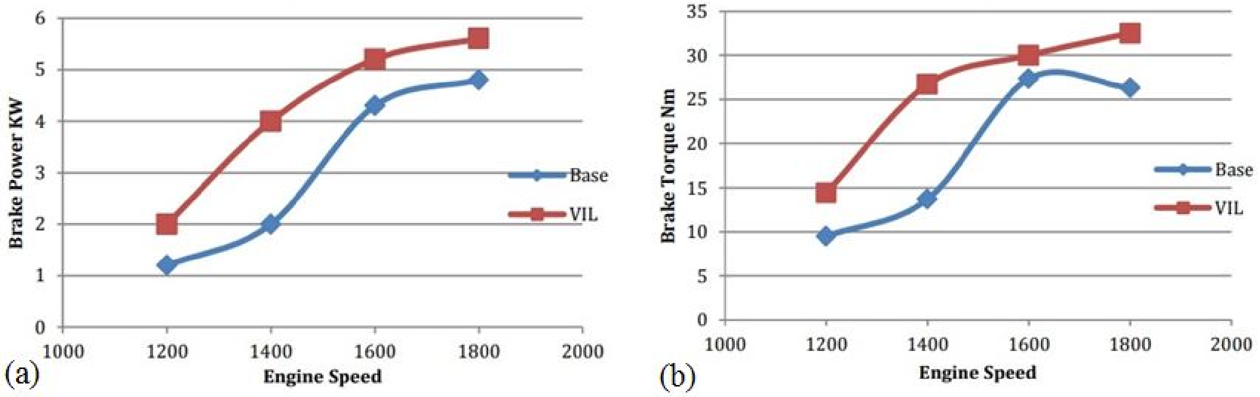


Figure 7. (a) Increase in braque power, (b) Increase in brake torque. Source: (JAGADISHSINGH and JADHAV, 2016).

According to JAGADISHSINGH and JADHAV (2016), the results showed an increase of minimum 5% and maximum 25% in the volumetric efficiency using the variable intake length system, the increase in brake power and brake torque at rated engine speed is near about 17% and 10%, respectively. A last example of a variable geometry admission system application, is the work of SODRÉ *et al.* (2008). The researchers used an single-cylinder engine, 4-stroke, spark-ignition, Water-Cooled, Displacement 661 cm^3, Max. power 50 kW and Max. torque 93 Nm. The researchers does not developed a simulation for their engine, but conducted experimental tests following the NBR ISO 1585 (ABNT, 1996) norm for experiments. As defined by the authors, in order to study the effects of the intake duct on the motor performance under study, three lengths of PVC material were used, with lengths of 300, 600 and 900 mm. A caliper rule was used to measure the dimensions and a ribbon saw to construct the prototypes. Performance curves were performed with the full throttle engaged to allow the throttle to be fully open throughout the test, providing the maximum flow of naturally aspirated air. All tests kept the coolant temperature at the engine outlet within a range of 82^oC $\pm$ 2^oC, relative humidity between 48% and 52%, oil temperature above 100^o C, barometric pressure around 910 mbar, the inlet air temperature at 20^oC $\pm$ 2^oC and the fuel pressure at 3.50 $\pm$ 0.02 bar. To determine the power in the reference atmospheric conditions, the observed (read) power was multiplied by a correction factor α (ABNT NBR ISO 1585), which remained around 1.12 in these experiments. The authors claim that from the engine speed of 4500 rev/min the inlet conduit, with the length of 300 mm, presented higher power values, the 600 mm length intermediate and 900 mm in length generated lower values Fig. 8(a). This effect can be explained by the loss of charge from the fluid friction with the conduit walls, being larger, as longer the conduit length is, which is known from fundamentals of fluid mechanics. They follow: that can be seen in Fig. 8(b). that the longer inlet conduit provides greater torque at lower rotational speeds. This result can be attributed to the improved volumetric efficiency of the longest conduit in this region of motor operation. This shows that, at low engine speeds, the larger the duct, the greater the inertial effect of the air mass.

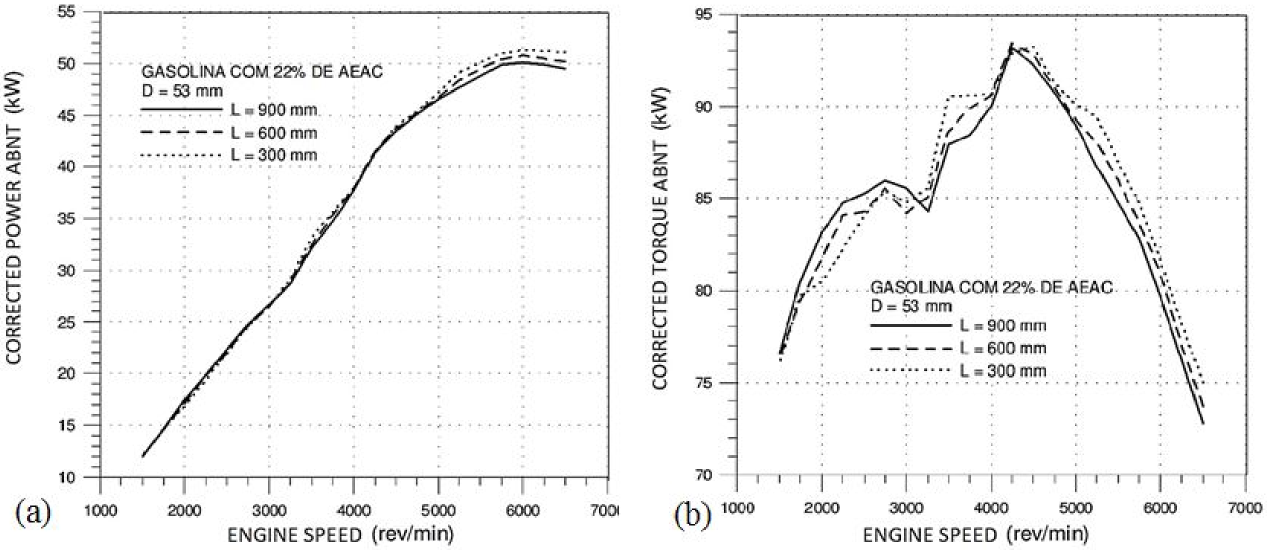


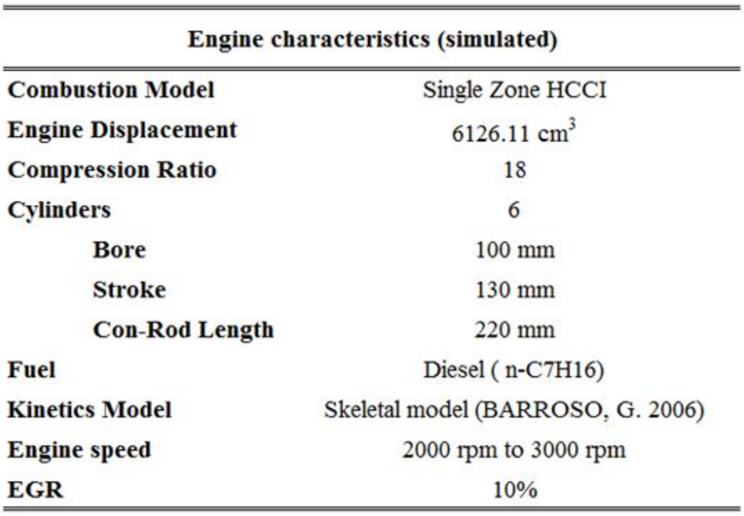
Figure 8. (a) Comparison of power by varying the length of the intake duct, (b) Comparison of torque by varying the length of the intake duct. Source: (SODRÉ *et al.*, 2008).

3. HCCI ENGINE VARIABLE-LENGTH INTAKE MANIFOLD SIMULATION

In order to assess the effect of a variable-length intake manifold in a HCCI engine a numerical analysis was performed. The numerical simulation was done in the AVL Software R2017. The AVL-BOOST (Virtual Engine Development - 0D modeling) for internal combustion engines simulations was used. Homogeneous Charge Compression Ignition HCCI is a low temperature combustion strategy that has successfully yielded high thermal efficiencies and low emissions (FATOURAIE *et al.*, 2008). There is abundant literature about the HCCI combustion process and its implementation on internal combustion engines FATOURAIE *et al.* (2008) , RAPP *et al.* (2013) , SILKE *et al.* (2008) , KALGHATGI and HEAD (2006) , SAXENA and BEDOYA (2013) , BARROSO (2006) and references there in). In this work, the focus is to analyze the effect of variable length intake manifold in engines, and of this form the authors will not go deep in details about the HCCI modeling methodology.

3.1 HCCI engine characteristics for numerical analysis

The AVL-BOOST engine model and its characteristics is described in Fig. 9. The detailed kinetics model used was developed by BARROSO (2006), is composed by 26 chemical species among 66 elementary reactions. The detailed kinetics model, named as skeletal model, was developed for n-heptane (n-C7H16) and it is suitable as Diesel surrogate.



Engine characteristics (simulated)	
Combustion Model	Single Zone HCCI
Engine Displacement	6126.11 cm^3
Compression Ratio	18
Cylinders	6
Bore	100 mm
Stroke	130 mm
Con-Rod Length	220 mm
Fuel	Diesel (n-C7H16)
Kinetics Model	Skeletal model (BARROSO, G. 2006)
Engine speed	2000 rpm to 3000 rpm
EGR	10%

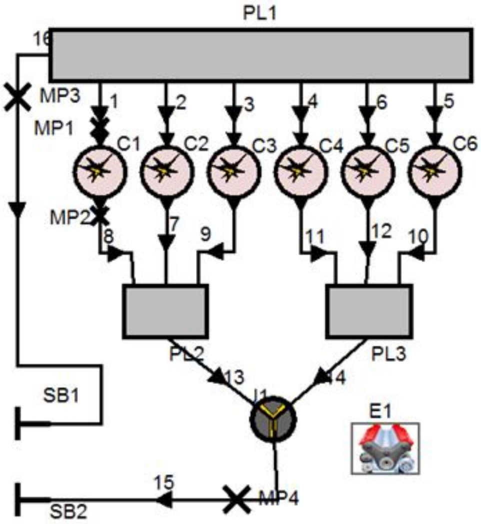


Figure 9. Engine characteristics and AVL-BOOST model. Source: This work

3.2 Engine performance predictions

Fig. 10 show the (a) volumetric efficiency and (b) specific fuel consumption (brake) predictions for the five intake lengths analyzed in this work, covering the 2000 to 3000 rpm engine speed range. A numerical result shows that for L = 875 mm the volumetric efficiency is better than the others lengths tested at least a big part of engine speed range. L = 448 mm shows the lowest BSFC along all the engine speed range.

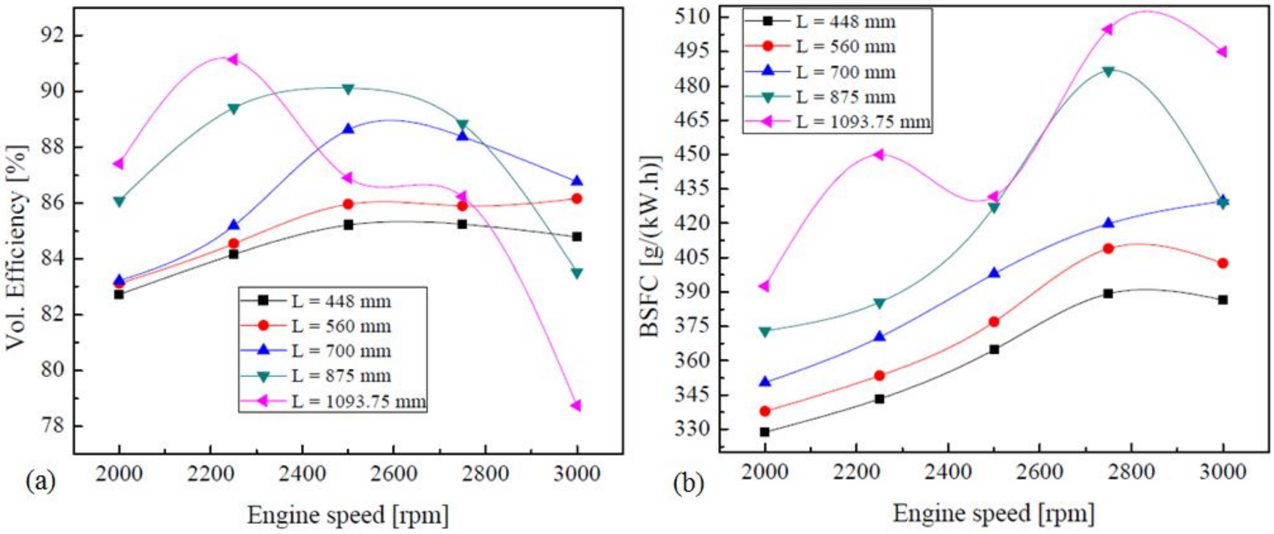


Figure 10. Numerical predictions of (a) Volumetric efficiency, (b) Specific Fuel Consumption (Brake). Source: Source: This work

Fig. 11 show the (a) power and (b) torque predictions for the five intake lengths analyzed in this work, covering the 2000 to 3000 rpm engine speed range. It can be observed that the best power and torque predictions are for L = 448 mm, regarding Fig. 10(b), the best intake length was just for L = 448 mm.

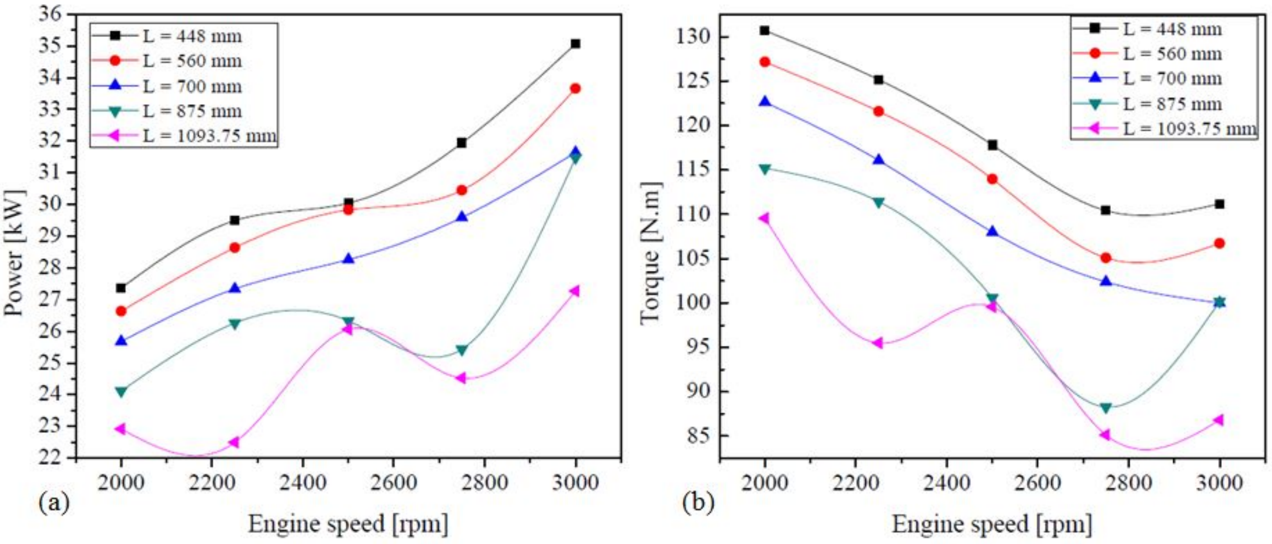


Figure 11. Numerical predictions of (a) Power, (b) Torque. Source: This work

Fig. 12 show the numerical (a) Peak firing temperature and (b) Combustion start predictions for the five intake lengths analyzed in this work, covering the 2000 to 3000 rpm engine speed range. It can be observed that for length of L = 448 mm the values of peak firing temperature does not spread (not so much) in the engine speed range. Just for L = 1093.75 mm is predicted the biggest temperature difference of about 120 K (2250 to 3000 rpm). The combustion start is also influenced by the intake length, the biggest difference is about 5 grad angle for L = 1093.75 mm.

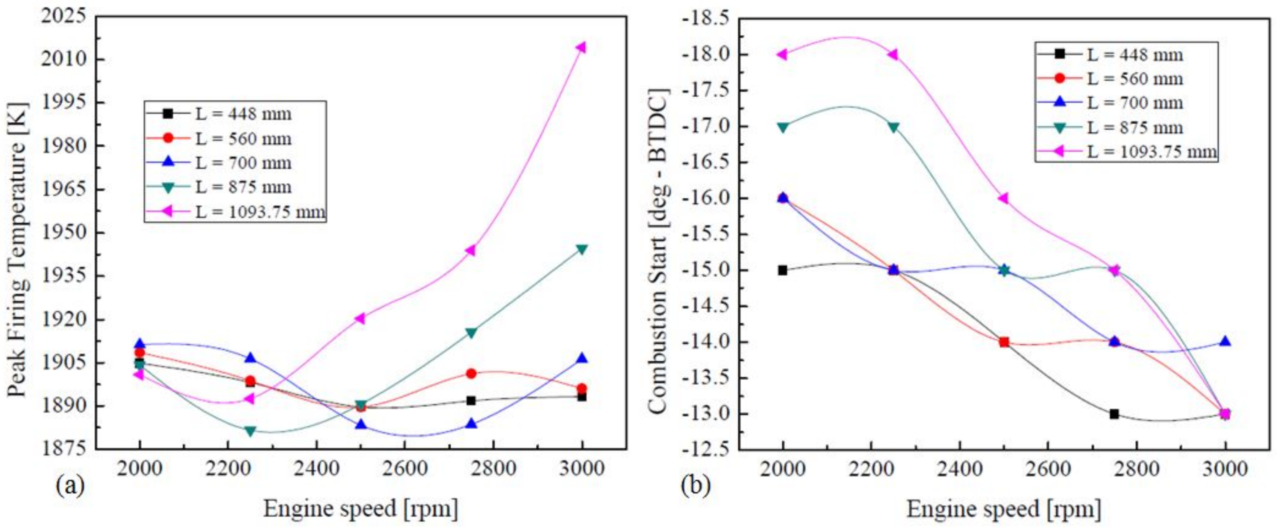


Figure 12. (a) Peak firing temperature and (b) Combustion start. Source: This work

Fig. 13 show the numerical predictions of pressure at intake valve for (a) L = 448 mm, full cycle (b) L = 448 mm, among IVO and EVC. (a) L = 1093.75 mm, full cycle (b) L = 1093.75 mm, among IVO and EVC. It can be observed the same excitation trends like MORSE *et al.* (1938) and HARRISON (2004).

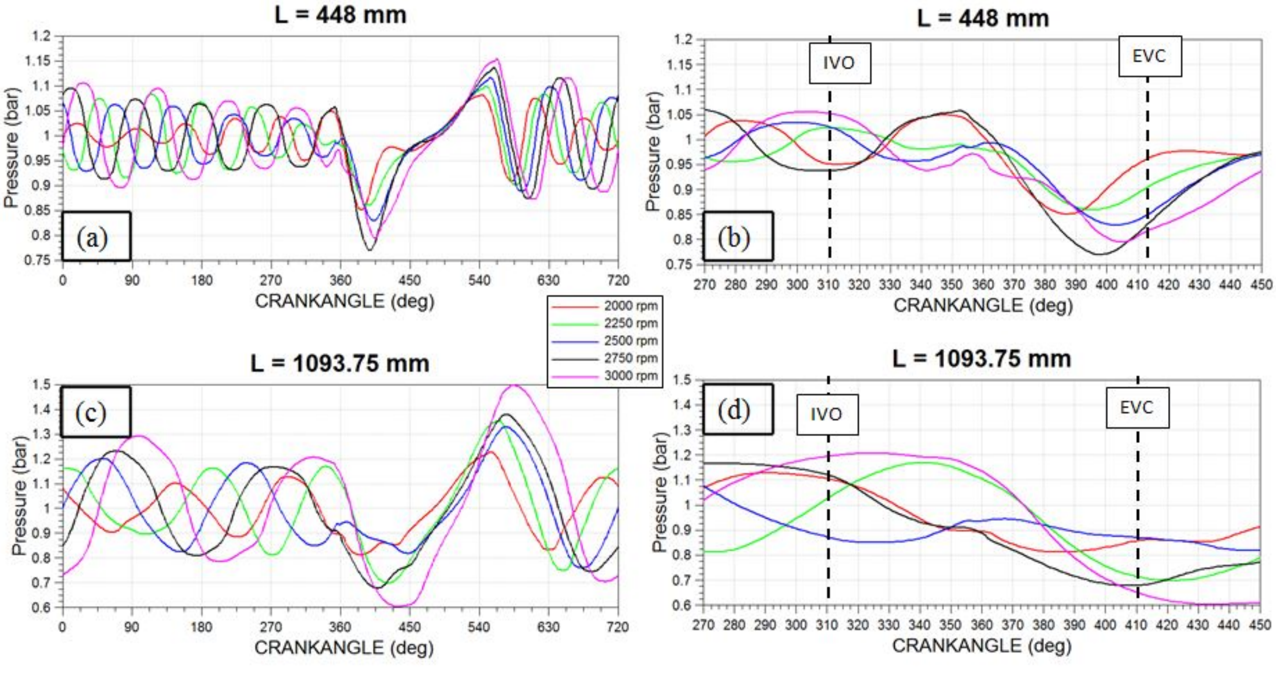


Figure 13. Pressure at intake valve: (a) L = 448 mm, full cycle (b) L = 448 mm, among IVO and EVC. (a) L = 1093.75 mm, full cycle (b) L = 1093.75 mm, among IVO and EVC. Source: This work

4. CONCLUSION

Based on theories as Helmholtz resonator and ram charging, is pretty clear that the geometry of an intake system is fundamental for the good breathing of the engine, increasing its volumetric efficiency, and consequently, its performance. The equations of acoustics, vibrations and fluid mechanics give a pack of tools that presents a lot of possible combinations for inlet tracts, helping to define, for example, the best diameter and length for a certain purpose of the engine. The problem with static intake systems is that one condition will always be sacrificed to favor another, for example, the decision to use a shorter intake pipe to increase volumetric efficiency in low engine speed will harms efficiency on higher RPMs, as could be seen on HEISLER (1995) work. The ideal ratio between the resonant frequency of the Helmholtz resonator and the engine speed defined by ENGELMAN (1953) as a constant around two, can only be applied for one specific engine speed, and will limited the potential of the engine, unless the length of the ducts could variate. The variable-length intake manifold comes up as a solution, resulting in a more elastic engine, not only increasing its power, torque and volumetric efficiency, but also enhancing its performance on a very larger range of engine speed than compared with the static intake version. The numerical simulation shows that it is possible to optimize the length of intake manifold (runners in this case) in order to get benefits in terms of volumetric efficiency, specific fuel consumption, power and torque. The pressure at intake valve port shows the oscillating character of pressure depending of the runner length. The simulation results point out important parameters for the HCCI operation and realization, the fact of capture and temperature difference of about 120 K for the same runner length in the engine speed range is an important result for the engine cooling system project. The numerical simulation shows that it is possible to apply the variable-length intake manifold optimization method in order to set the best parameters for the best HCCI operation.

5. ACKNOWLEDGMENTS

The authors acknowledge the AVL AST University Partnership Program for the license of the full software access and support to the Internal Combustion Engines Laboratory LABMCI/UFSC

6. REFERENCES

BARROSO, G., 2006. *Chemical Kinetic Mechanism Reduction, Multizone and 3D - CRFD Modelling of Homogeneous Charge Compression Ignition Engines*. Master's thesis, ETH, Zurich, Zurich.

BRUNETTI, F., 2013. *Motores de combustão interna*. Blucher, São Paulo.

CEVIZ, M.A., 2007. "Intake plenum volume and its influence on the engine performance, cyclic variability and emissions". *Energy Conversion and Management*, Vol. 48, pp. 961–966.

ENGELMAN, H.W., 1953. *Surge Phenomena in Engine Scavenging*. Ph.D. thesis, University of Wisconsin, Wisconsin, USA.

FATOURAIE, M., KARWAT, D.M.A. and WOOLDRIDGE, M.S., 2008. "A numerical study of the effects of primary reference fuel chemical kinetics on ignition and heat release under homogeneous reciprocating engine conditions". *Combustion and Flame*, Vol. 163, p. 79âĂŞ89.

HARRISON, M. F.and DUNKLEY, A., 2004. "The acoustics of racing engine intake systems." *Journal of Sound and Vibration*, Vol. 271, pp. 959–984.

HEISLER, H., 1995. *Advanced Engine Technology*. SAE, U.S.A.

HEYWOOD, J.B., 2000. *Internal combustion engine fundamentals*. McGraw-Hill, New York.

JAGADISHSINGH, B.G. and JADHAV, N., 2016. "Effect of variable length intake manifold on performance of ic engine". *International Journal of Current Engineering and Technology*, Vol. 5, pp. 47–52.

KALGHATGI, G.T. and HEAD, R.A., 2006. "Combustion limits and efficiency in a homogeneous charge compression ignition engine". *International Journal of Engine Research*, Vol. 7, pp. 215–236.

MORSE, P.H., BODEN, R.H. and SCHECTER, H., 1938. "Acoustic vibrations and internal combustion engine performance". *Journal of applied Physics*, Vol. 9.

PEREIRA, L.V., 2008. *Estudo experimental da influência de um ressonador de volume variável na massa de ar admitida por um motor de combustão interna*. Ph.D. thesis, UFMG, Belo Horizonte/MG.

POTUL, S., NACHNOLKAR, R. and BHAVE, S., 2014. "Analysis of change in intake manifold lengt and development of variable intake system". *INTERNATIONAL JOURNAL OF SCIENTIFIC AND TECHNOLOGY RESEARCH*, Vol. 3, pp. 223–228.

RAPP, V.H., CANNELLA, W.J., CHEN, J.Y. and DIBBLE, R.W., 2013. "Predicting fuel performance for future hcci engines". *Combustion Science and Technology*, Vol. 185, pp. 735–748.

SAXENA, S. and BEDOYA, I.D., 2013. "Fundamental phenomena affecting low temperature combustion and hcci engines, high load limits and strategies for extending these limits". *Progress in Energy and Combustion Science*, Vol. 39, pp. 457–488.

SILKE, E.J., PITZ, W.J. and WESTBROOK, C.K., 2008. "Understanding the chemical effects of increased boost pressure under hcci conditions". *SAE Int. J. Fuels Lubr.*, Vol. 1, pp. 12–25.

SODRÉ, J.R., COSTA, R.C. and SILVA, R.H., 2008. "Efeitos do comprimento do conduto de admissão na performance de um motor de combustÃo interna". *I Jornada Científica e VI FIPA do CEFET*, Vol. 6.

THOMPSON, M.P., 1968. *Surge Phenomena in Engine Scavenging: Non-Mechanical supercharging of a Four Stroke Diesel Engine*. Ph.D. thesis, Ohio State University, Ohio, USA.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.