VARIABLE INTAKE VALVE LIFT ON A PORT FUEL INJECTED ENGINE AND ITS EFFECTS ON IDLE OPERATION

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INTRODUCTION

As an energy source, from the standpoint of power density, stored energy and autonomy, the internal combustion engine still remains today an appropriate and attractive solution for ensuring mobility. Engines have improved dramatically over the past two decades, and they will continue to improve [18]. The current scientific developments described in [21] suggest that there could be 6–15% improvements in internal combustion fuel efficiency in the coming decade, although the filters required to meet emission legislation reduce these gains.

For quite some time, CO_2 emissions and their impact on the greenhouse effect have become a topic of debate [18]. In the late 1990s, the European, Japanese and Korean automotive manufacturers (ACEA, JAMA and KAMA) adopted a voluntary commitment to reduce average CO_2 emissions from new passenger cars sold to 140 g/km by 2008 with a view to reaching the EU target of 120 g/km by 2012 [18, 25]. In 2007, the European Commission underlined that progress had been made towards the 140 g/km target by 2008 but that the Community objective of 120 g CO_2/km would not be met by 2012 in the absence of additional measures. Therefore, in 2009, the EU laid down CO_2 emission performance standards through Regulation (EC) No 443/2009 [24]. This regulation stipulates that each OEM in the industry needs to achieve an average of 130 g CO_2/km by 2015 and 95 g CO_2/km by 2020 or face a punitive fine for exceeding the limits [23, 24].

Historically, engine selection for light vehicles consists in choosing either the spark ignition engine (SIE) or the compression ignition engine (CIE). While the diesel engine has made enormous progress in recent years and features good fuel economy, the gasoline engine still lags behind from this point of view. Of the two technologies, SIE is however the most likely to attract investment over the next decade. Already, many radical technical solutions (e.g. gasoline direct injection - GDI, variable valve actuation - VVA, variable compression ratio - VCR, Downsizing, Atkinson-Miller cycle) have been lately revealed and some have been applied in mass production [2, 3, 5, 8, 12, 13, 15, 16, 17, 21, 22]. Their purpose is to eliminate the inefficiencies that for the past century have largely been accepted as inevitable.

During most of its life, a passenger car engine is run under low loads and speeds. It is known that load reduction in SIE is traditionally accomplished by introducing additional losses during the intake stroke by means of a throttle plate. In these operating points, the overall engine efficiency decreases from the peak values (already not very high) to values that are dramatically lower (sometime even below 10%). An obvious conclusion would be to look for technical solutions able to offer better efficiency, such as throttle-free actuation, for instance.

Nowadays, two methods are being intensively investigated in order to obtain unthrottled operation: GDI, featuring load control by means of lean burn possibilities (see [22] or Mitsubishi GDI, VW FSI or Mercedes CGI), and VVA [2, 3, 5, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17]. Both techniques promise a significant improvement in fuel economy.

However, only VVA still allows the use of the less expensive conventional exhaust gas after treatment (TWC), whereas lean GDI needs the more expensive extra treatment of nitrogen oxide (deNOx).

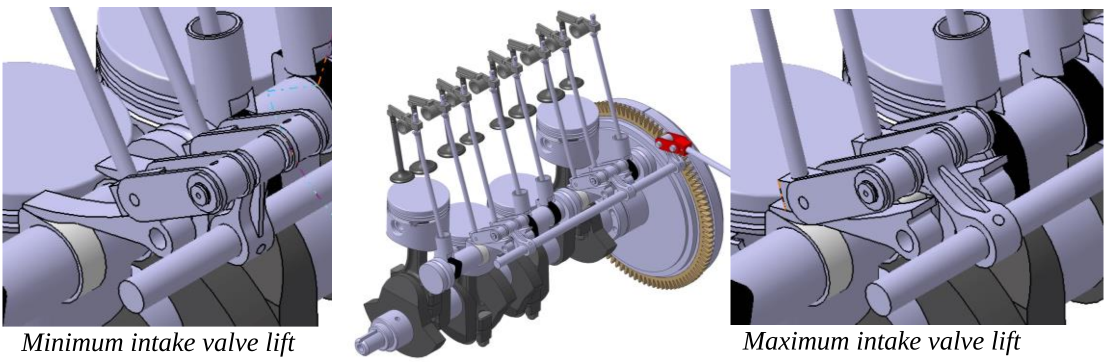
For some time there has been growing interest in throttle-less operation by means of VVA. Many scientific studies have been published on this subject, epitomized by BMW's Valvetronic-Vanos system, still the only continuously VVA system in mass production since 2001, able to offer throttle-less engine load control. According to papers [3, 16], a 15% fuel economy improvement was obtained on NEDC with a 1.8 litre engine.

Given this context, the paper presents a variable intake valve lift (ViVL) mechanism, used to enhance fuel consumption in the idle and low part loads operation [6, 7, 8, 9, 10, 11]. This mechanism is currently self-regulated thanks to a hydro-mechanical system, which is the subject of a French patent [19], and allows a continuous intake valve lift variation during engine operation, making throttle-less operation possible [9].

This study presents the initial experimental results obtained within the framework of several research contracts financed by the Romanian Council for Scientific Research (CNCSIS) and the French Agency for Research (OSEO-ANVAR) [9, 10, 11].

1. MECHANISM DESCRIPTION AND OPERATION

As can be seen from figure 1, the system comprises a side mounted camshaft and overhead valves, featuring a classical push-rod/rocker type mechanism. Spark ignition engines with the camshaft in the engine block (i.e. "push-rod engines") are still being built in the USA and are in use in even larger quantities throughout the world. This layout is low-end in design and can be produced at low cost [17].

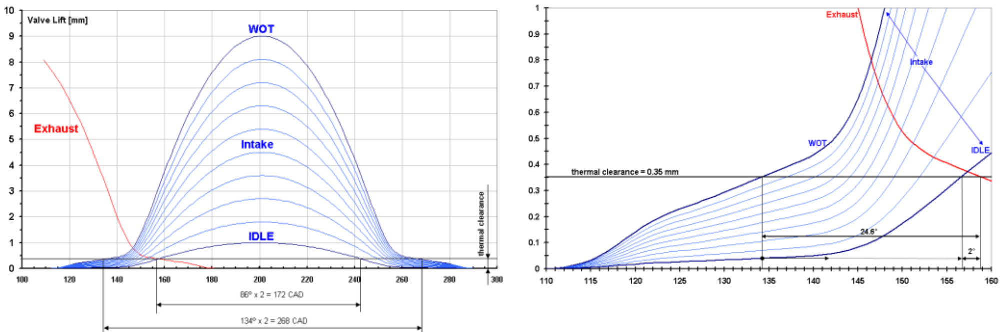


Minimum intake valve lift *Maximum intake valve lift*

Figure 1 The ViVL mechanism

The mechanism presented hereafter (figure 1) is able to adjust the intake valve lift thanks to an assembly consisting of an oscillating follower and a translational skate. The skate's position on the follower is adjusted with the help of a connecting rod and a control lever, so that every intake valve lift (iVL) can be achieved continuously between minimum and maximum values during operation. The control lever's position is given by a hydraulic cylinder, fed with oil from the engine's main oil gallery [5, 6, 7, 8, 9, 10, 11, 19].

The results of the intake valve displacement calculus as a function of cam rotation angle for different positions of the control lever are shown in figure 2. The ViVL mechanism also leads to variable valve overlap and opening duration through the thermal clearance, which induces a lost motion. A hydraulic lash adjuster could no doubt be used in order to avoid having a non-controlled parameter, which is altered by the engine temperature, thus complicating the problem.



a. variable valve opening duration *b. variable valve overlap*

Figure 2 *Intake valve displacement*

The maximum intake valve law was imposed so as to be the same as the baseline engine from which this prototype originated, meaning that the goal is not to alter the engine operation at WOT but to improve it at low part loads and speeds. In the particular situation of using this ViVL mechanism, the unknown was the intake cam profile able to provide the maximum iVL mentioned above. An analytical synthesis was therefore performed. Afterwards, the partial intake valve laws corresponding to the part loads were obtained [6]. For the minimum iVL encountered at idle operation, the mechanism was designed to function if necessary at near-zero value. In this study, the minimum lift was set at 1 mm as it is stated in [16] that in most parts of the european driving cycle, the valve lift is below 1.5 mm and that a lift of 4 mm is reached only briefly in the higher speed part.

Mechanically speaking, ViVL provides some advantages particularly in the operating area corresponding to urban traffic (i.e. the most frequently encountered operation during the vehicle’s lifetime):

- the lower the valve lift, the lower the spring force i.e. less energy is consumed to compress the springs;
- the lower the valve lift, the lower the energy lost to overcome the friction between the valve stems and their guides;
- the lower the valve lift, the lower the equivalent mass and force at the cam level (figure 3) [6].

These three features mean improved mechanical efficiency and engine reliability.

As concerns the latter, figure 4 presents the variation in equivalent mass at the cam level with the intake valve lift.

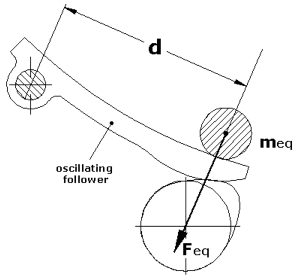


Figure 3
Equivalent mass on the cam level

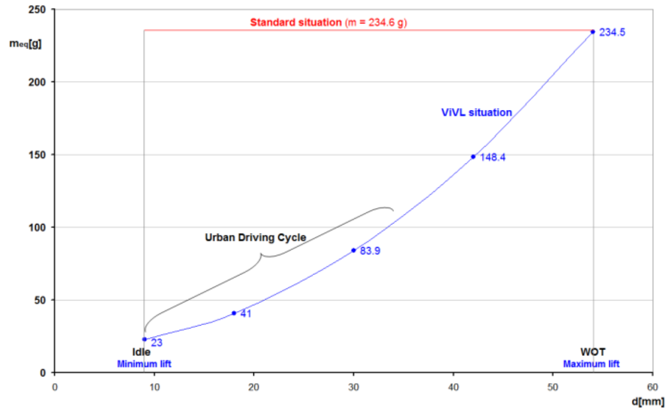


Figure 4 Equivalent mass at the cam level vs. intake valve law

Hence, it can be seen that at WOT the equivalent mass in the ViVL situation is equal to that of the standard system (i.e. without ViVL), while in the operating area specific to an urban driving cycle, the ViVL system provides much smaller values for the equivalent mass.

TEST BENCH RESULTS

The study was conducted on a 1.4 L, 4-cylinder in-line (77 mm stroke, 76 mm bore and geometric compression ratio 9), port-injected, spark ignition engine, which was equipped for acquiring the instantaneous in-cylinder pressure. Data acquisition and analysis of cycle-related parameters were performed with AVL Indimodul Hardware and AVL Concerto software. Engine testing was conducted over 200 complete engine cycles for each operating point. A p-V diagram displayed in real time was used to visually monitor combustion quality, which was judged statistically with the CoV of IMEP.

The parameters of the engine's injection and ignition management system were also modified in order to optimize the engine operation according to the new intake valve lift. Mapping, data acquisition and analysis were performed with INCA software.

Calibration of a standard engine management system is not an easy task and it already involves considerable engineering resources. Adding a new technology to a standard engine, such as the ViVL mechanism presented above, will introduce a greater level of complexity when addressing engine calibration. This is because of the additional degrees of freedom these systems come with. For example, an engine mapping, containing 2 main maps (one for the injection time map and the other one for the spark advance map) x 225 operating points, with 10 iVL will give 4500 points to analyze.

This paper presents the very first results of the attempt to optimize at stoichiometric value ($\lambda = 1$) the idle operation of the prototype engine with the new intake valve lift employed, i.e. the minimum one. It was decided to start with idle operation as this is where the maximum percentage improvement in fuel economy due to the use of low lifts is expected. All the tests were performed with the throttle plate closed, idle speed being achieved by correspondingly actuating the idle motor valve.

The reasons for not trying to approach idle with throttle-free operation are presented below. When considering gas exchange processes in the spark ignition engine, the goal is to conduct them so that the pumping losses are lower. As stated above, VVA could help in this direction (see the throttle-less load control). However, putting this idea into practice is quite challenging, especially at idle operation. For example, applying the strategy presented in figure 2 could ensure throttle-less load control but, as is also shown hereafter, it is accomplished at the expense of greater pumping losses, as the peak value of the intake valve lift needs to be quite low (<< 1 mm). In March 2006 [9], the prototype presented in figure 1 was able to operate unthrottled with a maximum intake valve lift of 0.5 mm but with an air excess of 1.6 (lean mixture); this means that to ensure stoichiometric operation, less air should be allowed to be drawn into the cylinder, which can be achieved by reducing even further the valve lift. If this strategy is chosen, pumping losses will increase even more.

A VVA strategy suited for unthrottled operation at part loads and that ensures smaller pumping losses consists in lowering the intake valve lift (not as much as before) with a highly restrained opening duration and in closing the intake valve very early. This is what BMW is doing thanks to its Valvetronic - BiVanos mechanism [2, 3, 16]. The problem with such a strategy is that once the intake valve closes, an expansion occurs during the rest of the intake stroke, which lowers the temperature (sometimes even to the limit of condensing the fuel) and diminishes the intake charge energy [3]. Greater velocity means greater energy, which accelerates combustion, and at idle operation, this phenomenon is very important as combustion stability is the key issue here. In order to avoid these phenomena, BMW operates at idle with late intake valve opening (LIVO) and a valve lift, which falls at 0.37 mm. This results in flow velocities approaching the speed of sound with a favourable effect on combustion. However, the pumping losses are greater than those obtained with the classical throttled engine, according to [3].

Therefore, one idea to emerge from this literature review is that even though minimal pumping losses should be one of the goals, this must not be done while impairing other aspects such as mixing process, charge kinetic energy prior to spark etc.

Thus, in this paper, two comparative situations were xperimentally explored: 850 rpm idle operation at maximum iVL vs. 850 rpm idle operation at minimum iVL, both at the same spark advance (12 CAD). For the minimum iVL, two other values for the spark advance (27 and 29 CAD) were subsequently tested in order to improve the engine operation even further.

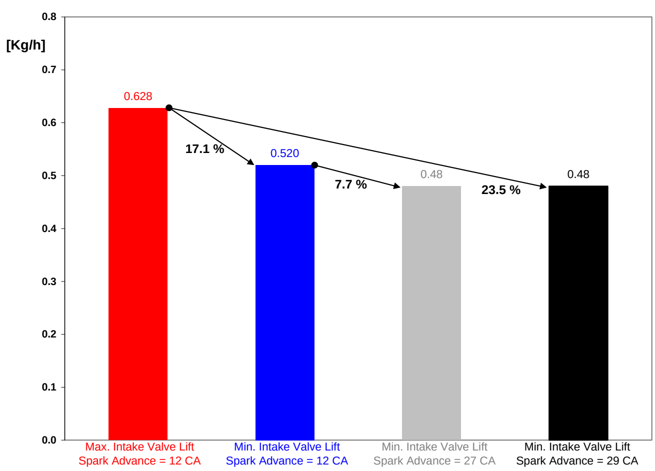


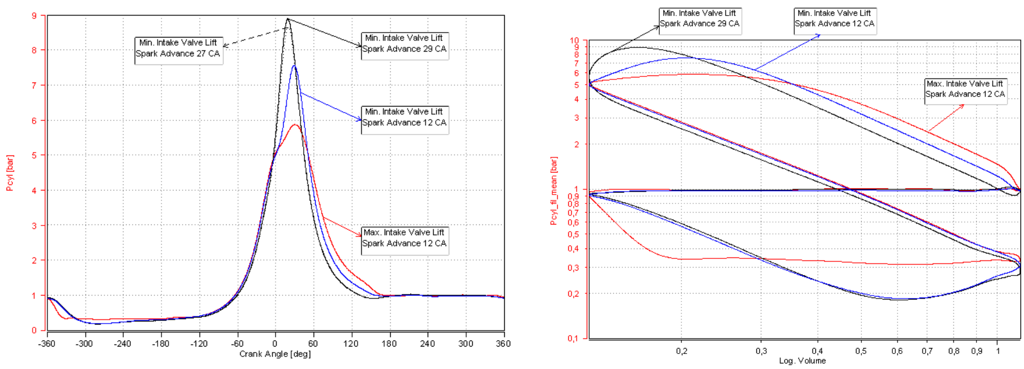
Figure 5 Fuel consumption results

Fuel consumption is shown in figure 5. Different reasons underpin these results, such as improvement of the fuel-air mixing process and air motion as the valve lift lowers. Moreover, as stated before, the energy to overcome the friction between the valve stems and their guides and the energy necessary to compress the valve springs decrease considerably as the lift lowers (e.g. between the maximum lift of 9 mm and the minimum one of 1 mm, the reduction in the energy necessary to compress the valve springs falls by almost 92 %). In order to differentiate between these two phenomena (the energetic one over the mechanical one), figure 9 presents eloquent results.

Increasing the spark advance from 12 to 27 or 29 CAD causes a further reduction in fuel consumption due to combustion, which occurs more around TDC.

In order to observe this in greater detail, figure 6, a and b shows typical indicated diagrams for the cases mentioned above. As the 27 CAD spark advance situation (the black dotted line in figure 6, a) is close to the 29 CAD spark advance situation (the black continuous line in figure 6, a), it was discarded from figure 6, b.

It can be seen that lowering the iVL leads to an increase in the pumping losses (figure 6, *b*). In fact, at 12 CAD spark advance, PMEP increased by about 5.8 % when running at idle with minimum iVL compared with the maximum lift. However, as seen in figure 5, there is a non-negligible fuel economy benefit in the minimum lift situation even in spite of increased pumping, meaning that the intensified flow speed underneath the intake valve (thus, the improved mixing process) and the reduced mechanical energy needed to compress the valve springs at lower lifts have strong effects upon the fuel consumption.



a. pressure over CA *b. LOG p – LOG V diagram*

Figure 6 Indicated diagrams at 850 rpm idle operation

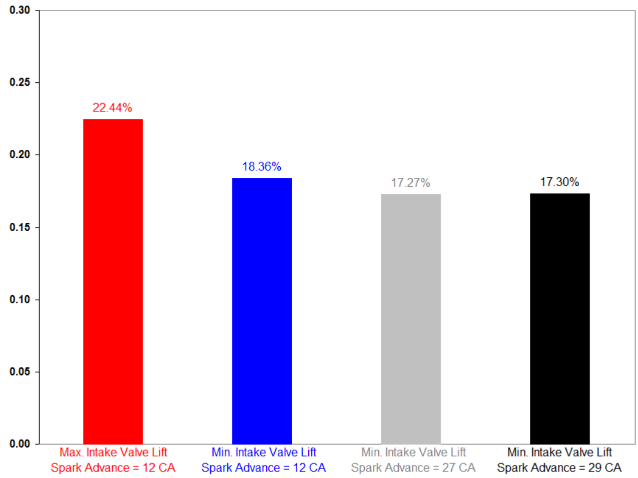


Figure 7 Engine filling efficiency

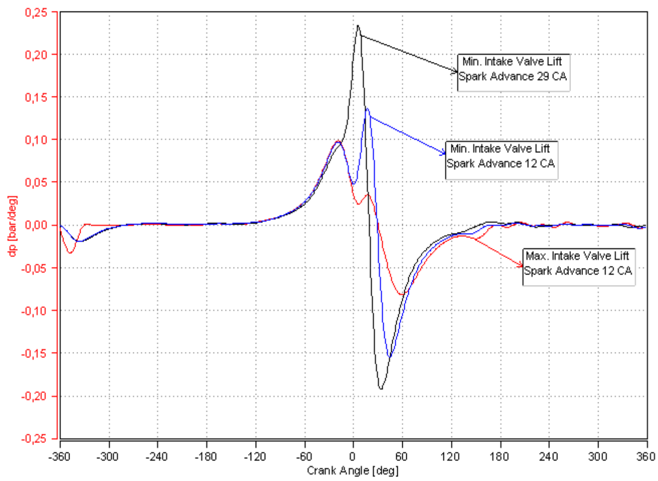


Figure 8 Pressure rise evolution over the CA

The effect of increasing PMEP can also be observed when analyzing the engine filling efficiency, which falls from 22.4 % at maximum iVL to 18.4 % at minimum iVL, both at the same 12 CAD spark advance (figure 7).

The peak pressure (figure 6, a) and, especially, the maximum pressure rise (figure 8) also increased significantly when using minimum lift, proving once again the virtues of a better mixing process and air motion. On the other hand, the two peaks of the pressure rise recorded at minimum valve lift with 12 CAD (blue curve in figure 8) indicate a small spark advance (combustion begins too late – see figures 9, 10 and table 1). Increasing the spark advance from 12 to 29 CAD, for instance, eliminated the two peaks mentioned before (black curve in figure 8).

Another advantage of operating with low lifts at idle operation is the reduction in the cyclic dispersion: CoV of IMEP decreased from 8.8 % to 5.4 % when passing from maximum to minimum lift at 12 CAD spark ignition advance and to 3.5 % at minimum lift and 29 CAD. This is also due to the reduction in the amount of internal EGR as the valve overlap decreases when the intake valve lift is lowered (figure 2, *b*).

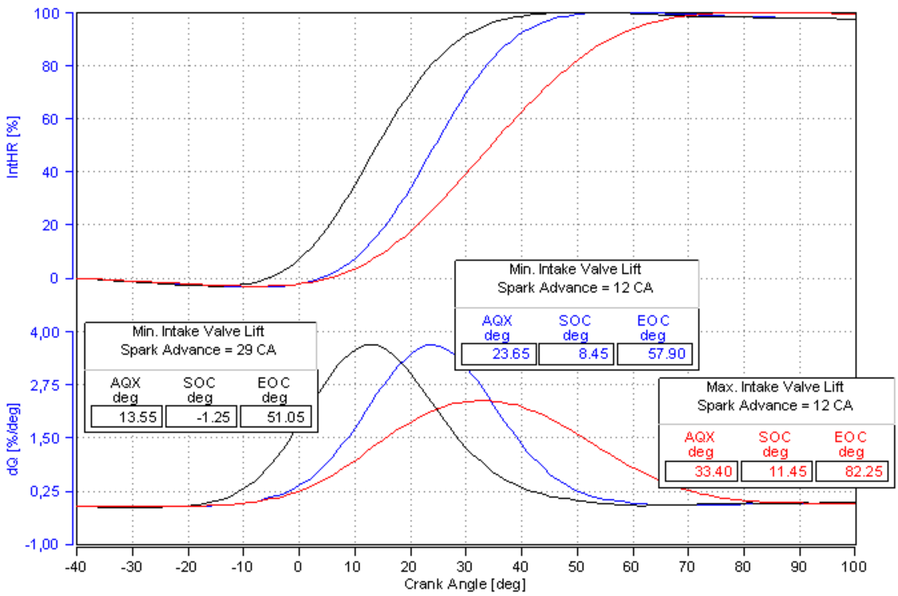


Figure 9 Heat release and rate of heat release evolutions

Figure 9 presents the heat release and rate of heat release evolution for the above-mentioned cases. Due to the difficulties in evaluating the convective coefficient, thermal losses to the engine walls were not considered, which means that the real end of combustion (EOC) cannot be found.

In figure 9, EOC is the moment when the zero value of the rate of heat release occurs. Conversely, the start of combustion (SOC) is conventionally taken as the moment when 5% mass burnt fraction takes place.

Figure 9 shows that with minimum lift, the heat release rate increases, which means that the main contributor to the fuel consumption reduction presented in figure 5 is the improvement in the air-fuel mixing process and air motion through lowering the valve lift.

To better assess combustion in the 3 cases considered, some more information is given in figure 10 and table 1.

Thus, when analyzing maximum iVL vs. minimum iVL at the same 12 CAD spark advance, it can be seen that the crank angle duration of all the combustion phases decreases, causing a better fuel economy, as seen in figure 5. As before, reducing the amount of internal EGR when lowering the intake valve lift is responsible for a more stable and faster combustion. When increasing the spark advance at the same minimum iVL, the combustion phase durations increase, which perhaps indicates a non-optimal value for the spark advance, though the fuel consumption still decreased (figure 5). Obviously, in order to clarify these aspects, there is a need for a more refined parametric study to determine the optimum spark advance for this particular operation.

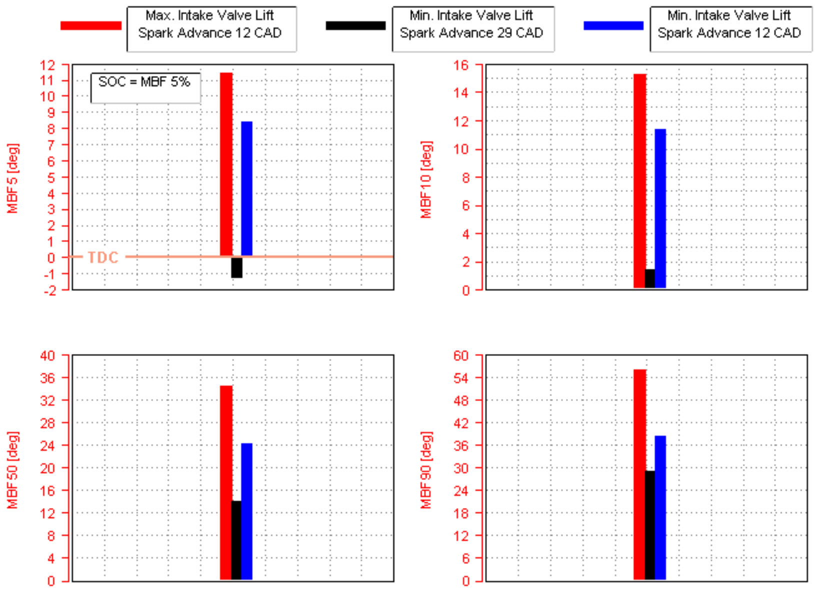


Figure 10 CAD at which some predefined per cent of energy is converted (5, 10, 50 and 90 %)

Table 1 Combustion phases' duration

Combustion phases	**Max. Intake Valve Lift**	**Min. Intake Valve Lift**	
	Spark Advance = 12 CAD	*Spark Advance = 12 CAD*	*Spark Advance = 29 CAD*
Ignition point – SOC	23.5	↘ 20.5	↗ 27.8
Ignition point – α_{pmax}	42.3	↘ 41	↗ 48
α_{pmax} – EOC	52	↘ 28.9	↗ 32.1
SOC – EOC	70.8	↘ 49.5	↗ 52.3

SLEEP&START STRATEGY

Idle operation is a prominent feature of real world driving, especially in congested city traffic. For vehicle homologation, standardised driving cycles are used. For instance, figure 11 presents the first portion of the NEDC/NMVEG cycle, corresponding to the urban driving cycle (UDC). This consists of four identical parts, which are said to represent city driving in Europe, having a total period of 240 seconds of idling (i.e. 31% of UDC total time).

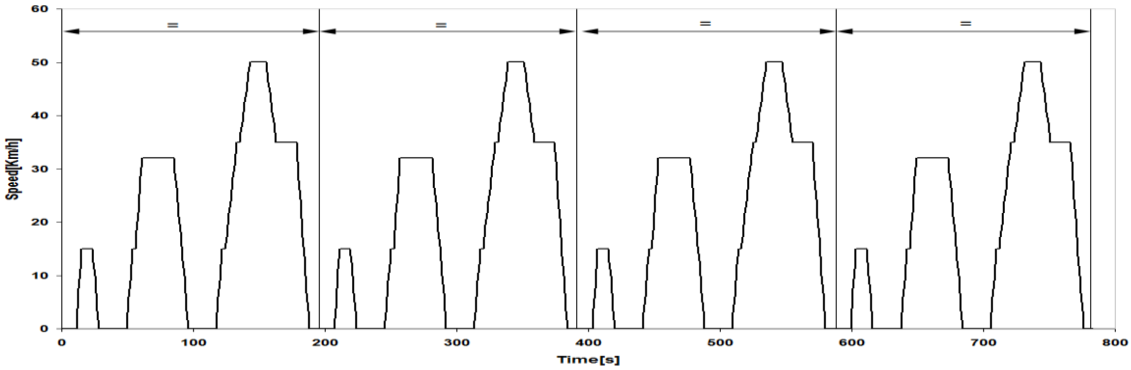


Figure 11 The UDC from the NEDC

In order to save fuel and thus to cut CO_2 emissions, currently the Stop&Start function is usually implemented on vehicles [1, 4, 14, 20, 21]. According to papers [1, 20, 21], a 5 to 10% potential in fuel economy on UDC can be attributed to this function.

The Stop&Start function marks the very first step toward hybridisation and is relatively straightforward. However, when implementing it on a vehicle some issues arise, which are briefly summarized below:

- the need for additional electric motors able to ensure HVAC within the stop phases;
- the need for a battery monitoring system, as SoC and SoH are the key issues in this area [10];
- the need to monitor the vacuum within the vehicle's assisted-braking system;
- the need to take into account the engine cool down during the stop phase;
- the need to have acceptable re-start times and vehicle acceleration from zero kmph.

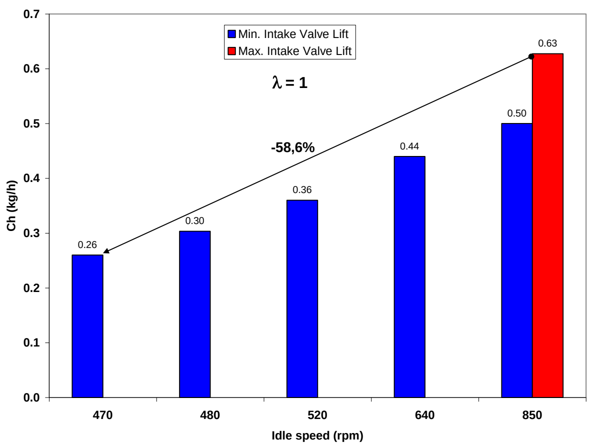


Figure 12 Fuel consumption reduction obtained by Sleep&Start strategy

In order to avoid the above problems, a so-called Sleep&Start strategy could be used, i.e. once an internal combustion engine features a ViVL system, the use of very low idle speeds could be envisaged the moment the vehicle has come to a stop.

In other words, once a ViVL system has been installed on an engine, it should be used in every possible way in order to obtain a high benefits/cost ratio.

The experiments on this particular matter showed that when idling at 470 rpm, at 1 mm intake valve lift and stoichiometric value, an almost 60% reduction was recorded with respect to the situation at 850 rpm and maximum intake valve lift (figure 12). The idle speed of 470 rpm was found to be the lowest limit at which proper cooling and lubrication were still possible using the same water and oil pumps as the standard engine. In fact, even though speeds lower than this could be obtained due to the low iVL, it seems they were insufficient to ensure a minimum water flow for the cooling needs of the engine.

If this strategy is applied only on the UDC, then 24.6 g of fuel is saved with respect to the standard situation illustrated in red in figure 12 (see the relation below):

$$FC_{Gain}\ [g] = \frac{Idle\_time_{UDC}\ [s]\cdot(C_{h\_standard\_idle} - C_{h\_Sleep\&Start})[Kg/h]}{3.6}$$

$$FC_{Gain} = \frac{240\cdot(0.63-0.26)}{3.6} = 24.6\ g$$

If one takes as a reference the fuel consumption obtained on a UDC by a typical 5-door, C-class vehicle, which has a conventional 1.4 liter, 4-cylinder port-injected spark ignition engine, 75 hp and a 5-speed manual transmission with a kerb weight of 1130 kg, i.e. 277 grams of fuel, then the Sleep&Start strategy accounts for an 8.8% fuel reduction.

Within the context presented by this paper, the Sleep&Start strategy presents a certain interest in order to yield even greater fuel economy benefits from the ViVL mechanism.

3. CONCLUSIONS AND FUTURE WORK

In comparison with other solutions that might be considered as alternative automotive energy sources, the internal combustion engine still remains the most convenient option, and research efforts are currently being directed toward achieving increased efficiency throughout the entire automotive engine operating range.

In more than a century of spark ignition engine development, complete automatic regulation of air-fuel ratio and spark advance have been accomplished. Nowadays, taking into account the wide variety of the automotive engine’s working regimes, the only way to obtain lower consumption and pollution is to provide the engine with automatic control systems such as the one presented in this paper. From this point of view, VVA offers many opportunities for improving the engine’s performance in areas such as fuel economy and emissions, and it seems will become a must-have on gasoline engines.

This paper has presented the initial experimental results obtained when approaching idle operation with different configurations of the intake valve timing system. These results revealed an improvement in fuel economy at idle operation of around 20% in spite of an increased pumping work. As stated, this gain in fuel economy was mainly generated by an increased airflow velocity of the fresh mixture into the cylinders, causing an improvement in the fuel-air mixing process and, in the end, better combustion. Thus, one could say this is the most significant element in the equation of fuel consumption reduction at idle operation.

Moreover, additional work is still to be performed in order to ascertain the full potential of ViVL for fuel economy, such as more refined parametric studies in order to map the injection and ignition management system for each iVL from the whole operating engine field.

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ABBREVIATIONS

ACEA – Association des Constructeurs Européens d'Automobiles;
AQX – crank angle at which the rate of heat release is maximal;
CA – crank angle;
CAD – crank angle degrees;
CGI – charge guided injection;
CIE – compression ignition engine;
C_h – hourly fuel consumption, [Kg/h]
d – skate's displacement on the oscillating follower, [mm]
EC – European Commission;
EGR – exhaust gas recirculation;
EOC – end of combustion;
EU – European Union;
$FC_{\_gain}$ – fuel consumption gain, [g]
FSI – fuel stratified injection;
GDI – gasoline direct injection;
HR – heat release;
HVAC – heating-ventilation and air-conditioning;
IMEP – indicated mean effective pressure;
iVL – intake valve lift, [mm];
JAMA – Japanese Automobile Manufacturers' Association;
KAMA – Korean Automobile Manufacturers' Association;
MBF – mass burnt fraction;
m_{eq} – equivalent mass at the cam level, [g]
NEDC – New European Driving Cycle;
OEM – original equipment manufacturers;
PMEP – pumping mean effective pressure;
SIE – spark ignition engine;
SoC – state of charge;
SoH – state of health;
TDC – top dead center;
TWC – three way catalyst;
UDC – urban driving cycle;
VCR – variable compression ratio;
ViVL – variable intake valve lift;
VVA – variable valve actuation;
WOT – wide open throttle.

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