

Reduction of Cold-Start Emissions through Valve Timing in a GDI Engine

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ABSTRACT

This work examines the effect of valve timing during cold crank-start and cold fast-idle (1200 rpm, 2 bar NIMEP) on the emissions of hydrocarbons (HC) and particulate mass and number (PM/PN). Four different cam-phaser configurations are studied in detail: 1. Baseline stock valve timing. 2. Late intake opening/closing. 3. Early exhaust opening/closing. 4. Late intake phasing combined with early exhaust phasing. Delaying the intake valve opening improves the mixture formation process and results in more than 25% reduction of the HC and of the PM/PN emissions during cold crank-start. Early exhaust valve phasing results in a deterioration of the HC and PM/PN emissions performance during cold crank-start. Nevertheless, early exhaust valve phasing slightly improves the HC emissions and substantially reduces the particulate emissions at cold fast-idle. The combined strategy consisting of late intake and early exhaust phasing shows a considerable reduction in both the cold crank-start HC and PM/PN emissions of 30%. In fast idle, the HC and PM emissions respond differently to the different valve timing strategy. The combined late IVO and early EVC configuration with moderate combustion phasing retard gives the best HC and PM emissions and reasonable engine stability.

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INTRODUCTION

Gasoline direct injection (GDI) engines have been rapidly adopted in the markets during the past decade, going from virtually 0% to a 38% market share in the US [1] and over 30% in the EU [2]. GDI engines have a number of advantages for reducing fuel consumption; however, the direct liquid injection poses some emissions challenges, especially for HC and PM during the cold-start phase. Figure 1 shows the tailpipe HC and PM/PN emissions during the FTP-75 for two representative GDI engines [3, 4]. In the representative case of Fig. 1, the cold-start phase is responsible for 97% of the HC emissions and 77% of the PM/PN emissions.

During cold-start, the combustion chamber walls are at a lower temperature than the saturation temperature of most of the fuel species; the result is the formation of fuel films which fail to completely evaporate prior to combustion. The fuel that does manage to evaporate from the spray and the films could form overly rich regions due to incomplete mixing; these regions are responsible for the high levels of HC and PM/PN emissions during cold-start. Additionally, the cold temperature increases the solubility of gaseous fuel into the oil layer prior to combustion. After combustion, the higher burned gas temperature and the low HC content of the burned gases favors desorption of the fuel back into the bulk gases, thereby providing an additional source for HC emissions. The low piston temperature also results in larger crevice volumes, increasing the amount of gaseous fuel escaping combustion. Lastly, the post-flame oxidation rates of the HC that managed to escape the main

combustion event, and of the particles formed during combustion, are reduced due to increased heat transfer from the bulk gases to the cold cylinder walls.

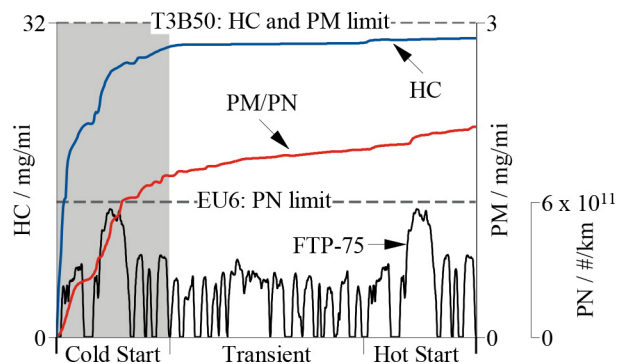


Figure 1. Cumulative tailpipe HC and PM/PN emissions over the FTP-75 cycle for GDI engines. The HC data correspond to a 2010 vehicle equipped with a 3.5 liters turbocharged GDI engine and a low temperature TWC [3]. The PM/PN data correspond to a 2.4 liters naturally aspirated GDI engine without a GPF [4]. The HC limit of T3B50 assumes the same HC/NOx ratio as the T2B5 standard

This study is part of a wider effort undertaken at MIT to understand and mitigate the engine-out HC and PM/PN emissions during the cold-start phase [5, 6, 7, 8, 9]. This paper builds upon the findings and methodology of two previous studies on the 1st cycle emissions and fuel pathway during cold cranking [5, 6]. Additionally, it complements previous studies on emissions control through valve overlap [7], and through injection strategy [8, 9].

The goal of the present study is to quantify the potential of unconventional valve timing with large negative valve overlap (NVO) for reducing the engine-out HC and PM emissions during the cold crank-start and fast-idle phases of a GDI engine. With variable valve timing (VVT) systems, the selection of the de-energized position (parked position) of the camshafts is limited by the authority of the phasing system and the desired maximum intake advance and exhaust retard during warm operation. As the authority of VVT systems increases, new camshaft parked positions become possible. The merits of these parked positions for cold-start emissions control are discussed in this paper.

EXPERIMENTAL METHODOLOGY

Engine Set Up

The experimental study was carried out in a production 4 cylinder, 2 liter turbocharged GDI engine, featuring a centrally mounted spark plug, 4 valves per cylinder and a side mounted injector (see Table 1). The electromagnetic injectors have 6 holes each, an inclination of 25° respect to the horizontal, and a cone angle of 52° . The VVT system is hydraulically actuated, has an authority of 50°CA on each camshaft and allows the advancing of the intake valve timing and the retarding of the exhaust valve timing. For the investigations of delayed intake timing and advanced exhaust timing, the parked position of the camshafts had to be mechanically modified. The new parked positions of the camshafts were achieved by rotating the camshaft by 2 cam sprockets teeth. Since the cam sprockets have 46 teeth, a rotation of 2 teeth corresponds to a change in camshaft timing of approximately 31°CA .

Table 1. Specifications of the GM - LNF engine

Displacement	1998 cc
Bore / Stroke	86 / 86 mm
Connecting Rod	145.5 mm
Compression ratio	9.2:1
Fuel pressure	50 bar
Baseline inlet Valve Open / Close	$11^\circ\text{aTDC} / 61^\circ\text{aBDC} @ 0.2 \text{ mm lift}$
Baseline max. intake valve lift	10.3 mm @ $126^\circ\text{aTDC}_{\text{intake}}$
Baseline exhaust Valve Open / Close	$52^\circ\text{bBDC} / 10^\circ\text{bTDC} @ 0.2 \text{ mm lift}$
Baseline max. exhaust valve lift	10.3 mm @ $121^\circ\text{bTDC}_{\text{intake}}$

The fuel pressure was maintained at 50 bar using a hydro-pneumatic accumulator using nitrogen. This allows the fuel pressure to be set independently from engine speed, especially during cranking. The fuel used was a Tier II EEE certification gasoline with a carbon mass fraction of 86.5%, and 29% aromatics content. The fuel's RON and MON were 96.6 and 88.5 respectively. The Reid vapor pressure was 62.7 kPa with the distillation curve is shown in Fig. 2. The cold-start conditions were maintained by 3 independent chillers for the fuel, intake air, engine oil and coolant, maintaining all temperatures as close to 20°C as possible.

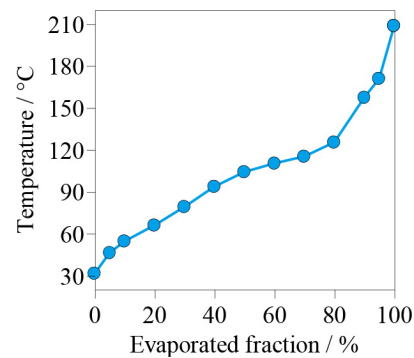


Figure 2. Distillation curve of the Tier II EEE certification gasoline used in the study

The exhaust composition was measured at the exhaust runner of cylinder 4 using fast response analyzers from Cambustion. The HC mole fraction was measured using an FFID unit, with a response time t_{10-90} of 1 ms, and a sampling position 8 cm from the exhaust valve. The CO and CO_2 mole fractions were measured with a fast NDIR unit, with a response time t_{10-90} of 8 ms, and a sampling position 6 cm from the exhaust valve. The PM and PN concentrations were measured using a fast particle spectrometer with a t_{10-90} of 300 ms, and a sampling point 15 cm from the exhaust valve. Additionally, the temperature and pressure of the working fluids were monitored at several positions. The locations of the different sensors are shown in Fig. 3.

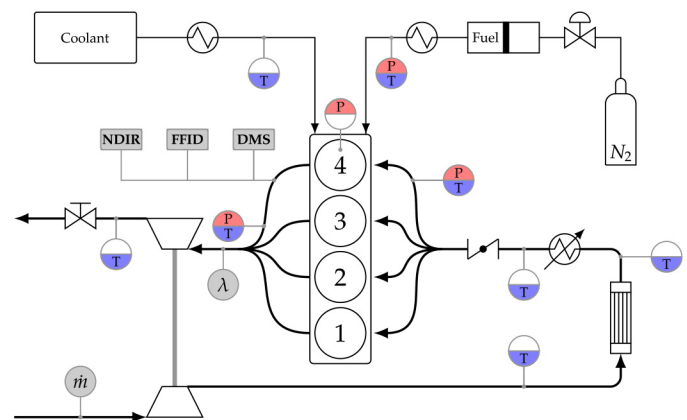


Figure 3. Diagram of the experimental setup and the sensor locations

The results presented in this paper deal with mass emissions of the aforementioned pollutants. The methodology to convert the mole fraction and concentration values to mass emissions is described in detail in a previous publication by the authors [5].

Experimental Conditions

For this study four different valve timing were investigated, corresponding to the different combinations of exhaust timing advance and intake timing retard, as shown in Fig. 4. The experimental matrix with the resulting valve timings is shown in Table 2.

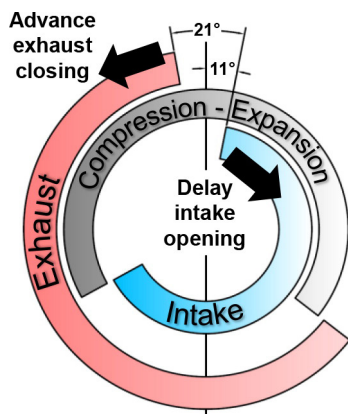


Figure 4. Baseline intake and exhaust timings and direction of phasing for the other investigated valve timings

Table 2. Experimental matrix

Case name	Intake timing @0.2mm lift	Exhaust timing @0.2mm lift
Baseline	IVO=11°CA aTDC IVC=61°CA aBDC	EVC=10°CA bTDC EVO=52°CA bBDC
Late IVO	IVO=42°CA aTDC IVC=92°CA aBDC	EVC=10°CA bTDC EVO=52°CA bBDC
Early EVC	IVO=11°CA aTDC IVC=61°CA aBDC	EVC=41°CA bTDC EVO=83°CA bBDC
Symmetric NVO (crank-start)	IVO=42°CA aTDC IVC=92°CA aBDC	EVC=41°CA bTDC EVO=83°CA bBDC
Symmetric NVO (fast-idle)	IVO=37°CA aTDC IVC=87°CA aBDC	EVC=36°CA bTDC EVO=78°CA bBDC

In order to cover the complete cold-start, two different sets of tests were carried out for this study: Cold crank-start and cold fast-idle.

To separate the effects of valve timing on the cold crank-start emissions from other parameters, the injected fuel mass for each cycle was adjusted to result in a similar combustion lambda during crank-start for all valve timing cases (see Fig. 5). The combustion lambda was calculated based on the CO and CO₂ mole fractions and disregarding the HC content [10]. Thus, the value represents the air equivalence ratio of the burned mixture. The spark timing for each cycle was adjusted for the initial 3 cycles, so that the point for 50% of heat release (CA50) was at a similar location for all valve timing cases studied. From the fourth cycle on, the spark timing was held constant for the rest of the crank-start process, resulting in later combustion phasing as the engine speed increased (see Fig. 5). For each valve timing setting, the throttle position was fixed throughout the cranking process at a position resulting in 2bar NIMEP at 1200 rpm (fast-idle conditions). For each experimental case, the injection timing was adjusted individually for the first three cycles and was chosen to minimize HC and PM emissions. From the 4th cycle on, the injection event took place during the mid-intake stroke (SOI=105°CA aTDC_{intake}) for all cases. Each experimental condition was repeated 5 times, and the results reported correspond to the average values.

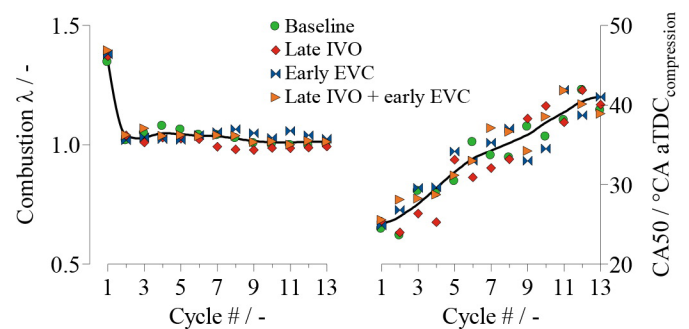


Figure 5. Combustion lambda and CA50 during the crank-start process for all four valve timings studied

Fast-idle engine management is an important part of the emissions control strategy during the cold start phase. During this quasi-steady period after crank-start, there should be sufficient exhaust enthalpy flow for a rapid warm-up of the TWC, while at the same time, maintaining low levels of pollutant emissions since the catalyst is not yet effective. For each valve timing case, the fast-idle experiments were carried out at a representative operating point summarized in Table 3. For the symmetric NVO case, the fast-idle valve timing differs from the one at crank-start (see Table 2) due to stability issues (see section on Fast Idle Results later).

Table 3. Fast idle condition

Engine speed	1200 rpm
NIMEP	2 bar
Lambda	1
External EGR	0 %
Coolant, oil and fuel temperature	20 °C
Start of injection timing	105°CA aTDC intake
Intake temperature	20°C
Fuel pressure	50 bar
Nominal number of cycles	150 cycles

COLD CRANK-START RESULTS

Crank-Start with Late Intake Valve Opening/Closing

The delayed intake valve timing has beneficial effects on the mixture preparation process in GDI engines at cold temperature. With intake timing delayed, the intake valves remain closed during the initial part of the intake stroke and produces a drop in cylinder pressure. Thus, the pressure differential across the valve at IVO increases, resulting in higher air velocity and increased turbulence during the initial portion of the intake stroke [11, 12, 13]. These flow features promote fuel-air mixing. Figure 6 shows the cycle simulation results for the air velocity at the intake valve with different IVO timings. Compared to the baseline, the peak air velocity can increase up to 8 times for the latest IVO studied; note that the maximum velocity is limited by the choked flow condition.