

Analysis of NO_x Emissions during Crank-Start and Cold Fast-Idle in a GDI Engine

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ABSTRACT

The NO_x emissions during the crank-start and cold fast-idle phases of a GDI engine are analyzed in detail. The NO_x emissions of the first 3 firing cycles are studied under a wide set of parameters including the mass of fuel injected, start of injection, and ignition timing. The results show a strong dependence of the NO_x emissions with injection timing; they are significantly reduced as the mixture is stratified. The impact of different valve timings on crank-start NO_x emissions was analyzed. Late intake and early exhaust timings show similar potential for NO_x reduction; 26-30% lower than the baseline. The combined strategy, resulting in a large symmetric negative valve overlap, shows the greatest reduction; 59% lower than the baseline. The cold fast-idle NO_x emissions were studied under different equivalence ratios, injection strategies, combustion phasing, and valve timings. Slightly lean air-fuel mixtures result in a significant reduction of NO_x. The engine-out emissions are highly sensitivity to combustion phasing. Initial retard results in lower mass NO_x emissions up to CA50 around 40 °CA aTDC-compression. After this point the increase in fuel consumption and the reduction on residual fraction reverse the trend leading to an increase in NO_x mass emissions for later combustion phasing. Moderate exhaust timing advance is beneficial for NO_x emissions and has no impact on the exhaust enthalpy flow.

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INTRODUCTION

The market penetration of gasoline direct injection (GDI) engines has increased rapidly over the past decade, going from virtually 0% in 2007 to over 46% market share in 2015 for the US passenger cars [1]. The accelerated market adoption of GDI has been driven by the light-duty vehicle (LDV) fuel economy standards, given the benefits of the technology for reducing fuel consumption by enabling turbo-downsized engine concepts. Simultaneously to the fuel economy regulation, new, and more stringent pollutant emissions limits will soon come into force and will be gradually phased in over the next decade. Figure 1 shows the past, present and future US federal limits for pollutant emissions that the fleets of LDV's manufacturers have to comply with. From 1994, and looking forward to 2026, the combined limit for NO_x and HC emissions, which in combination are responsible for smog formation, will see a reduction of over 96%. Similarly, the maximum PM emissions, which contribute to respiratory diseases, will reduce in 97% in the same time frame.

The mixture formation process of GDI engines at cold temperatures poses some emissions challenges that need to be addressed to guarantee the future of the technology in the context of stringent emissions standards. During cold-start, the combustion chamber walls are at a lower temperature than the saturation temperature of most of

the fuel species; the results are the formation of fuel films which fail to completely evaporate prior to combustion, and a heterogeneous fuel-air distribution.

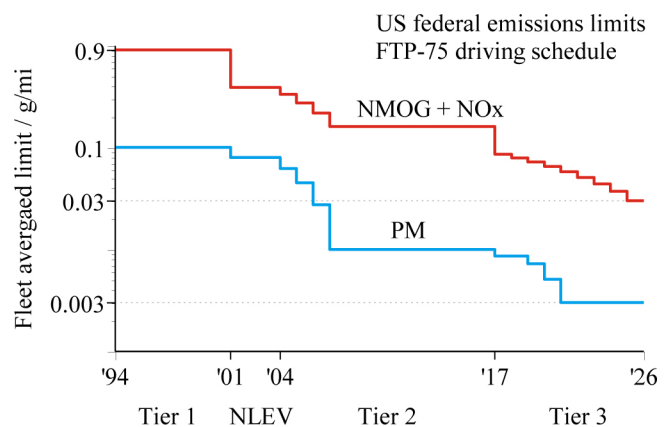


Figure 1. US federal fleet average emissions limits for light-duty vehicles over the FTP-75 driving schedule

Figure 2 shows the tailpipe NO_x, HC, and PM emissions during the FTP-75 for two representative engines [2, 3]. In the representative case of Figure 2, the cold-start phase contributes to 58% of the NO_x emissions, 79% of the HC emissions and 77% of the PM emissions.

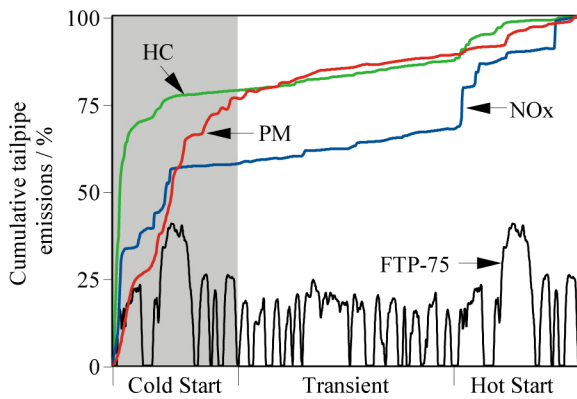


Figure 2. Relative cumulative tailpipe NOx, HC, and PM emissions over the FTP-75 cycle for gasoline engines. Data source: NOx and HC [2]; PM [3]

Zooming in to the cold-start phase, it is evident that the engine crank-start and cold fast-idle phases are responsible for a disproportionate share of the cold-start emissions. Figure 3 shows the performance and emissions characteristics of a typical cold crank-start of a GDI engine. The cumulative NOx, HC and PM emissions are referenced to the U.S. T3B50/ULEV50 limits, assuming the same HC/NOx ratio as the T2B5 standard.

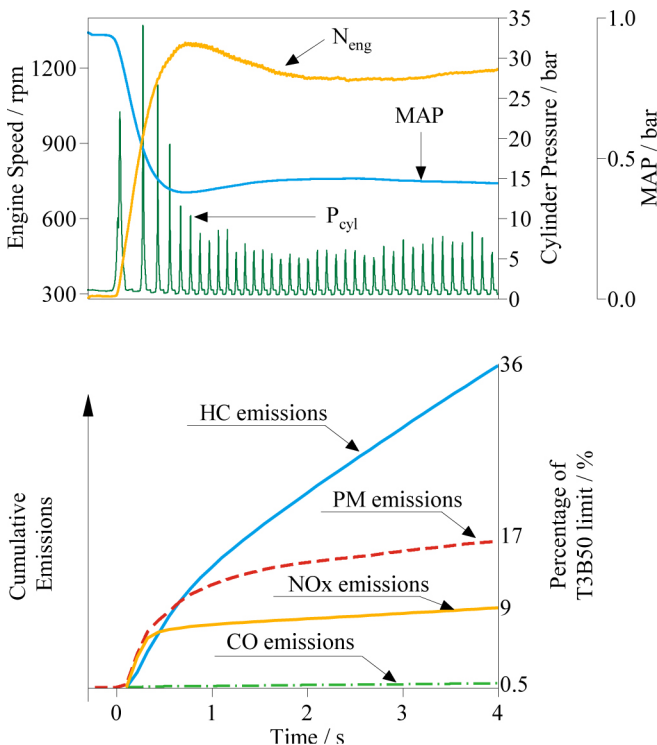


Figure 3. Cylinder pressure, engine speed, intake manifold pressure and cumulative emissions as percentage of the T3B50/ULEV50 limit during cold crank-start. The NOx and HC limits of T3B50 assumes the same HC/NOx ratio as the T2B5 standard.

The findings presented in this paper focus exclusively on the NOx emissions of GDI engines during crank-start and cold fast-idle. The results are divided in three main sections corresponding to the

cycle-by-cycle study, full crank-start analysis and cold fast-idle. The core of the investigation was carried out experimentally, with engine simulation providing support to understand the observed trends. This study is part of a wider effort undertaken at MIT to understand and mitigate the engine-out pollutant emissions during the cold-start phase of gasoline engines [4, 5, 6, 7, 8, 9, 10]. This paper follows the methodology developed by the authors in previous studies focusing on HC and PM emissions [4, 5].

EXPERIMENTAL METHODOLOGY

Engine Set Up

The engine used in this study was a commercial 4-cylinder, 2 liter engine, with side-mounted electromagnetic injectors. The injectors have a 52° cone angle, a 25° inclination from the horizontal and 6 holes. Further information on the engine geometry, including the baseline valve timing can be found in Table 1.

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
Intake Valve Open / Close	11°aTDC / 61°aBDC @ 0.2 mm lift
Max. intake valve lift	10.3 mm @ 126°aTDC
Exhaust Valve Open / Close	52°bBDC / 10°bTDC @ 0.2 mm lift
Max. exhaust valve lift	10.3 mm @ 125°aTDC

The fuel pressure during crank-start of a GDI engine depends significantly on engine speed; as the engine accelerates from the cranking speed to the speed flare the fuel pressure increases. The typical pressure for the initial engine cycles ranges between 30 and 70 bar [11, 12] and is heavily dependent on engine speed. To eliminate the influence of engine speed on the fuel pressure, the experimental setup for this study used a hydro-pneumatic accumulator pressurized to 50 bar by nitrogen. The fuel used was a Tier II EEE certification gasoline with a carbon mass fraction of 86.5%, 29% aromatics content and a Reid vapor pressure of 62.7 kPa. Three independent chillers for the fuel, intake air, engine oil and coolant were used to maintain the cold-start conditions, with all temperatures at 20°C.

The NOx mole fraction in the exhaust was measured using a fast response chemiluminescence detector (CLD). The CLD had a 10 to 90% time response of 4 ms. It uses a discharge generator for ozone (O₃) production. The reaction chamber, where NO and O₃ react to form NO₂ in an electrically excited state, is located approximately 30 cm from the tip of the sampling probe. The photons emitted by the NO₂ returning to its ground state are transferred to a photomultiplier detector through an optical fiber. Since the analyzer cannot measure NO₂ directly, a NO₂ to NOx ratio of 2% [13] was assumed.

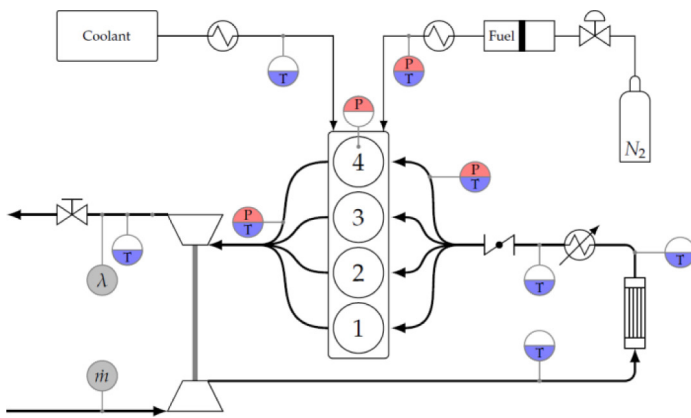


Figure 4. Diagram of the experimental setup and the sensor locations

To quantify the NOx emissions during cold-start, especially during the transient phase, it is necessary to relate the NOx mole fraction measurement to the mass flow rates of the exhaust stroke. The slow response of gas flow meters make them unsuitable for the cycle-resolved analysis sought in this work. Therefore, the exhaust mass flow rate was model, as shown in Eq. 1, using the cylinder pressure data and piston position as the model inputs.

$$\dot{m}_{exh} = - \left(\frac{1}{\gamma P_{cyl}} \frac{dP_{cyl}}{dt} + \frac{1}{V_{cyl}} \frac{dV_{cyl}}{dt} \right) m_{cyl} \quad (1)$$

Equation 2 shows the approach used for synchronizing the NOx mole fraction, as measured by the fast response CLD, with the modeled exhaust mass flow rate. It corrects for the transit time of the exhaust gases to the sampling location and for the intrinsic response time of the analyzer. The response and transit times are in the same order of magnitude; thus, the latter cannot be omitted.

$$m_{NOx,cycle} = \int_{t_{EVO}}^{t_{EVC}} \hat{x}_{NOx}(t + \tau(t)) \frac{MW_{NOx}}{MW_{exh}} \frac{dm_{exh}}{dt} dt \quad (2)$$

Experiment Description

Three different set of experiments were conducted to characterize the NOx emissions during cold-start in a GDI engine. First, the cycle-by-cycle emissions were studied individually for the initial 3 cycles, under a wide set of parameters. Second, the complete crank-start was investigated using different valve-timings. Lastly, the NOx emissions during the cold fast-idle phase were addressed.

Cycle-by-Cycle Experiments

The focus of this analysis was placed on cylinder 4. To eliminate the pressure, temperature and composition interactions from neighboring cylinders on cylinder 4, the engine was operated in single-cylinder mode. As a consequence, the engine was unable to achieve a speed transient that is representative of a 4-cylinder engine during crank-

start. To avoid this, the engine was torque-assisted by a 10 hp electric motor during the simulated crank-start experiments. As shown in Figure 5, the motor triggering point and speed-ramp were tuned to achieve similar speed traces between multi-cylinder and single-cylinder crank-start. The experiments start with the engine motoring at 280 rpm until steady state conditions are achieved. After the steady-state motoring, 1, 2 or 3 combustion events take place. Thereafter, engine is motored while the exhaust until the purging is completed and the engine returns to steady-state conditions. The throttle opening was fixed at the fast-idle position and the fuel injected was a function of the speed-density calibration.

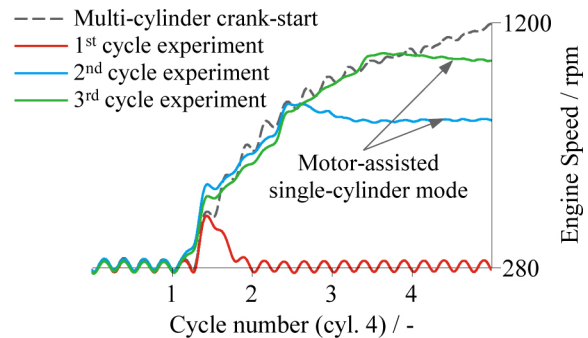


Figure 5. Representative engine speed and pressure traces for the 1 st (a), 2nd (b), and 3rd (c) cycle experiments

Five experiments were run for each experimental condition. The runs were separated by two minutes cool down period with the chilled water circulating to ensure the return to the initial conditions. Since only one, two, or three combustion events took place, experience showed that a two minute interval was sufficient. In-between runs, the engine was motored at 280 rpm to ensure the complete cylinder and oil layer purging. The results reported in this paper for each experimental condition correspond to the average of the five runs. The run to run coefficient of variation was approximately 15%. This value was however larger as NOx emissions were reduced due to the sensitivity, accuracy and resolution of the fast CLD at low NOx concentrations.

Complete Crank-Start Experiments

The impact on NOx emissions of four combinations of exhaust timing advance and intake timing retard, shown in Table 2, were investigated during cold crank-start. As shown in Figure 6, the effects of valve timing on NOx emissions were isolated by adjusting the injected fuel mass for each cycle in order to obtain a similar combustion lambda during crank-start for all valve timing cases. Furthermore, the spark timing for each cycle was adjusted, so that the point for 50% of heat release (CA50) was similar for all valve timing cases studied. For each valve timing setting, the throttle position was fixed throughout the cranking process at a position resulting in steady-state conditions of 2 bar NIMEP at 1200 rpm. Each condition was run 5 times; the results reported are the average values.