

# Fuel Accounting Analysis during Cranking and Startup using Simultaneous In-Cylinder and Exhaust Fast FID and NDIR Detectors

J. S. Cowart and L. J. Hamilton  
United States Naval Academy

## ABSTRACT

Optimization of in-cylinder air-fuel mixture preparation in Port Fuel Injected (PFI) engines during all phases of operation is critical for maximizing engine performance while minimizing harmful emissions. In this study, a Cooperative Fuels Research (CFR) gasoline engine is used to evaluate torque and measure in-cylinder and exhaust CO, CO<sub>2</sub> and unburned hydrocarbons under various fueling and spark conditions during crank and startup phases. Fast Flame Ionization Detectors (FFID) and Non-Dispersive Infra-Red (NDIR) fast CO and CO<sub>2</sub> detectors are used as the principle diagnostics. Additionally, detailed cycle resolved fuel accounting is performed to elucidate the fuel vaporization process from injection to exhaust. The majority of liquid fuel accumulation in the engine puddles occurs within 3 engine cycles after cranking begins. Post combustion UHCs were seen to reach levels of 40-80% of pre-combustion UHC values. Also, 12-25% of these post combustion UHCs failed to oxidize and were detected in the exhaust. Retarded spark timing has a modest effect on reducing exhaust UHC levels. Torque is found to be relatively insensitive to fueling within 5% of baseline-stoichiometric thus providing the engine developer adequate fueling flexibility to control emissions without significantly affecting performance.

## INTRODUCTION

Port Fuel Injected (PFI) Spark Ignition (SI) engines continue to provide one of the most economical fuel delivery methods for gasoline engines. Over the past few decades steady development efforts have improved the performance, efficiency and emission characteristics of these engines. During this time emission regulations have continued to tighten requiring precise fuel control during more of the engine operating window, notably during engine startup.

With the very low emission levels of today's PFI SI gasoline engines one of the few areas remaining for fuel

and spark control optimization is during the cranking and startup phases of the engine. This startup transient period is particularly challenging to calibrate and control due the rapidly changing engine speed and Manifold Absolute Pressure (MAP). Conventional steady state diagnostics do not provide adequate transient response, thus only fast cycle resolved measurements can provide insights. Improvements in emissions during these first few seconds is in need of further research in order to understand this critical period of engine operation.

The great challenge with PFI gasoline engines is due to the intake port fuel injection which can provide a significant transport delay of some of the injected fuel to the engine's combustion chamber. Much excellent work, during the past few decades, has provided fundamental insights into the mixture preparation process in PFI engines.

Qualitative visual studies have shown significant levels of liquid fuel remaining in the intake port and cylinder during cold start and warmup [1, 2, 3]. This residual fuel is often characterized as puddles remaining in the intake port and combustion chamber after the engine's cycle has completed. Quantification of these liquid fuel puddles has been performed to characterize the 'thickness' of these port [4] and in-cylinder [5] fuel films. Cool port and cylinder wall temperatures hinder fuel vaporization and promote quasi-stable films on these engine surfaces during engine startup and warmup.

A seminal study ten years ago by Imatake et al [6] using fast electronically controlled engine and throttle valves was able to quantify the mass of residual liquid fuel in the intake port and cylinder by 'trapping' the residual fuel at different points in the engine warmup process. This novel approach clearly showed that substantial fuel films exist during engine warmup. Further, the importance of fuel injection and engine operating conditions has been investigated [7, 8].

Fuel accounting during engine warmup has been performed by Shayler et al [9, 10]. This experimental



Documents

Document Sharing Hub

work is particularly challenging due to the very small absolute levels of fuel injected cycle by cycle during engine startup and warmup. Shayler has also made nice progress in quantifying the lost fuel to the engine's sump during engine warmup [11].

Cold start experiments can be complicated and time consuming with numerous operational and design variables included. In order to reduce this experimental effort, mixture preparation models can provide key physically based insights into this very complicated two-phase multi-component engine mixture preparation process. One of these physically based engine mixture preparation models has been developed and advanced by Curtis et al [12] to provide excellent understanding of cold start engine fuel preparation.

One area in this field of research that needs further development is that of the first few seconds of engine start. During this time period the rapidly changing engine speed and MAP creates great challenges with regards to fuel and spark delivery. Thus this study seeks to systematically quantify the effects of varied fueling and spark timings during the first five seconds of engine startup using fast in-cylinder and exhaust-based diagnostics. Analytical work was pursued to further understand the important fuel pathways of the injected fuel through the engine during this time frame.

## EXPERIMENTAL APPARATUS

The engine used in this study is a Cooperative Fuels Research (CFR) variable Compression Ratio (CR) gasoline engine. In this study CR = 9 was used. This engine was originally designed for Research method Octane Number (RON) testing and Motoring method Octane Number (MON) testing. The CFR unit contains a motor-generator for maintaining the engine at a constant 900 rpm during steady state operation. For these startup experiments, the CFR unit's motor was used for cranking. Over the first full engine cycle (the engine's rest position was manually set before each engine start to be Bottom Center Exhaust (BCE)), the average engine speed was measured to be ~250 rpm, which is only slightly faster than production engine starters. Due to the very large engine flywheel it takes the engine approximately seven engine cycles to achieve the steady state speed of 900 rpm. The CFR engine valve-train is standard with timings of IVO (Intake Valve Opening: 0.25 mm lift) = 10°ATC, IVC = 34°ABC, EVO = 40°BBC and EVC = 15°ATC. The engine coolant for each engine start (one start per day) was stable with the laboratory at 20°C +/- 1°C.

The original CFR carburetor and ignition system were removed. A conventional automotive coil and a production Ford™ 4-hole fuel injector were installed. This injector was calibrated using pure iso-octane fuel and collecting 1000 injection 'shots' into a closed

graduated cylinder at various fuel pulse widths. A new intake manifold was constructed using 30 mm diameter pipe containing a fuel injector port (directed at the intake valve), 3.7 liter transient damping tank and throttle (closed for all of the tests in this study). Figure 1 shows the experimental apparatus schematic.

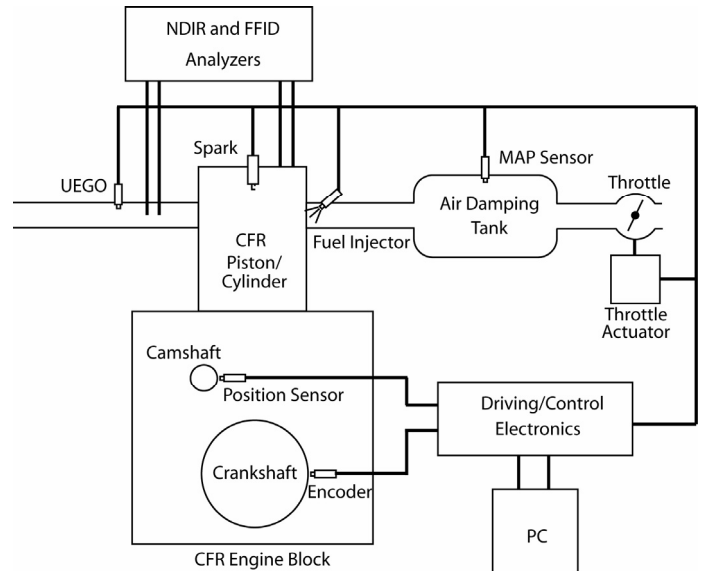


**Figure 1: Experimental Apparatus Schematic**

The fuel injector and ignition coil were all controlled by a custom engine controller with associated high power switching electronics external to the PC. The PC was equipped with a Cyber Research™ CYDAS1600 A/D card that interfaces with C code run on the PC. A BEI™ shaft encoder and an optical cam encoder were used by the PC for crank angle degree resolved engine position control. The engine was equipped with an automotive Manifold Absolute Pressure (MAP) sensor on the intake damping tank as well as a Universal Exhaust Gas Oxygen (UEGO) sensor in the exhaust.

Cambustion™ Fast Flame Ionization Detectors (FFID Unit: HFR500), and Non-Dispersive Infra-Red (NDIR Unit: NDIR500) Fast CO and CO<sub>2</sub> detectors were used as the principle diagnostics. Each Cambustion™ Unit has two sample heads, one for the in-cylinder measurement and one for the exhaust measurement. Each NDIR unit alternates measuring CO<sub>2</sub> and then CO continuously throughout the engine cycle. The Cambustion™ exhaust probes were located in the exhaust manifold just a few centimeters from CFR cylinder head. The Cambustion™ in-cylinder probes were located in a custom CFR engine plug, that replaces the conventional large CFR pressure transducer. This custom plug (located in the 'end-gas' region of the engine across from the spark plug) contained both 3 mm (outside diameter) sample probes and a mounting hole for the in-cylinder Kistler™ 6125B non-cooled pressure transducer. All of the data were collected on a separate National Instruments™ Labview data acquisition system using crank angle degree pulses from the BEI shaft encoder on the engine crankshaft. It is important to note that the exhaust sample is likely to be well mixed as the

location is approximately 15 cm downstream of the exhaust valve. The in-cylinder measurements (both FFID and NDIR: CO & CO<sub>2</sub>) are local to the end-gas region, however during the region of the engine cycle at which the data are extracted the signals are relatively stable, except for CO in-cylinder data which were not used in this study. The benefit of the in-cylinder signal is that due to the fast response of the Cambustion™ units coupled with the low engine speeds in this study intra-cycle information is also possible to attain as discussed next.

Calibration of the Cambustion™ FFID and NDIR units was performed before each engine start with the Cambustion™ calibration sampling probe attachments. These attachments allow in-situ calibration for the exhaust probes by flooding the sample probe inlets with calibration gases. The in-cylinder sampling heads were calibrated outside of the engine cylinder immediately before the engine startup test. Bottled zero and calibration gases were used, and are specified in the appendix.

Figure 2 shows a characteristic startup engine cycle with all of the key measured signals. Each of these displayed signals will be discussed next. Not shown are the crank angle degree pulses and Bottom Center Compression (BCC) pulses used for data triggering and cycle reference.

#### Fuel Pulse:

The fuel pulse was commanded to occur shortly after the Intake Valve Closed (IVC). This early Closed Valve Injection (CVI) timing was chosen to maximize fuel vaporization real time. The fuel calibration on a cycle by cycle basis will be described shortly.

#### FFID in-cylinder (FFID-in):

Two important pieces of information come from this continuous measurement. The FFID-in fuel vapor concentration plateau peaks ~210 cadeg (= 30 degATC) just before the main combustion event consumes the fuel-air charge in the end-gas. This signal can be used to determine the local Air-Fuel Ratio (AFR) just before flame arrival [13]. A second useful measurement from this signal occurs during the expansion and exhaust stroke. Post-combustion fuel vapor evolution occurs during the expansion and exhaust strokes of the engine. Evidence of post-combustion unburned hydrocarbon (UHC) evolution was seen and quantified recently by the authors in another paper [14]. Insights from using the FFID-in during this portion of the cycle will provide some interesting insights into the UHC generation phasing.

#### CO<sub>2</sub> in-cylinder (CO<sub>2</sub>-in):

Two important pieces of information also come from the CO<sub>2</sub>-in signal. The CO<sub>2</sub>-in signal shows a minimum value during the later half of the compression stroke up to just past TCC. This signal 'valley' will be used for residual fraction determination on the current engine cycle. In order to obtain the current cycle's residual fraction this minimum CO<sub>2</sub>-in is divided by the previous

cycle's post combustion CO<sub>2</sub> peak plateau concentration. Thus a cycle resolved residual gas determination can be made. Additionally, shortly after this minimum CO<sub>2</sub>-in period, the current cycle's post-main combustion carbon dioxide concentration can be measured from the peak-plateau level (~230-270 cadeg).

#### CO<sub>2</sub> exhaust and CO exhaust (CO<sub>2</sub>-ex and CO-ex):

These signals were adjusted for transport and sensor response delays and then averaged over the given cycle's exhaust stroke. Both of these signals were stable in magnitude during the exhaust stroke.

FFID exhaust (FFID-ex): The FFID exhaust signal was adjusted for transport delay and averaged over the exhaust stroke using a mass flow rate weighted exhaust model [1].

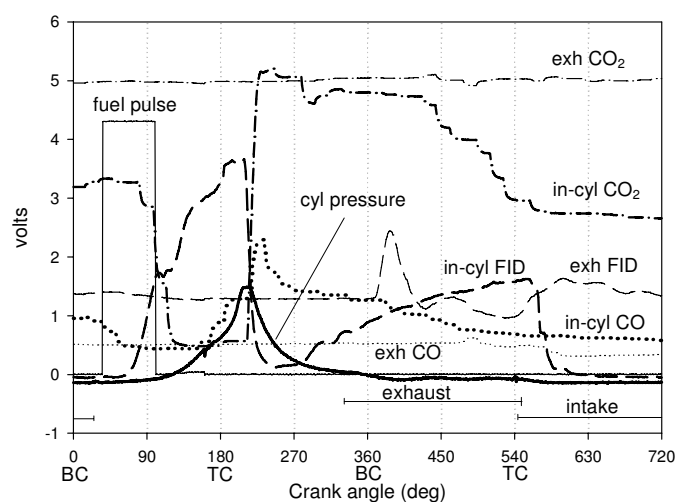


**Figure 2: Representative engine cycle with simultaneous raw diagnostic signals.**

## EXPERIMENTAL PROCEDURE

Daily cold starts were performed to iteratively calibrate the fuel control to its baseline level. Commercial grade premium gasoline was used throughout this study. Over a few dozen preparatory engine starts, the cycle-by-cycle fuel command was established by seeking to maximize the CO<sub>2</sub>-in post-combustion peak. With CO<sub>2</sub> peaking at stoichiometric mixtures it was believed that this level produced a stoichiometric in-cylinder charge. Spark was fixed at 20° BTC for the baseline case as this spark timing was observed to produce strong gross Indicated Mean Effective Pressure (IMEP<sub>g</sub>) cycles. It should be noted that this spark timing is somewhat advanced for the very low speed early engine cycles. A spark timing sweep was additionally performed later in this study in order to evaluate spark timing sensitivities.

Once the baseline condition was calibrated, daily starts were performed by systematically varying fuel and spark for a given start. In order to systematically vary the

effects of commanded fueling, additional cold starts were performed with fueling levels increased and decreased by a fixed fraction (e.g. 5% rich = 1.05 multiplier on every fuel pulse width for that start). A representative baseline start is shown in Figure 3. The commanded 'Lambda' of the baseline injected cycles is shown in this figure. It can be observed to increase (enlean) rapidly during the first ~6 engine cycles, then continue to enlean modestly for the next ~dozen cycles. After cycle number 20 the injected fuel pulse width is constant. In practice, continual slight commanded enleanment is pursued with longer engine operation times, however in this case the authors were interested to see the effects of constant fueling on emissions after the engine had reached RPM and MAP stability. Figure 4 shows the mass of fuel injected per cycle for each fueling case.

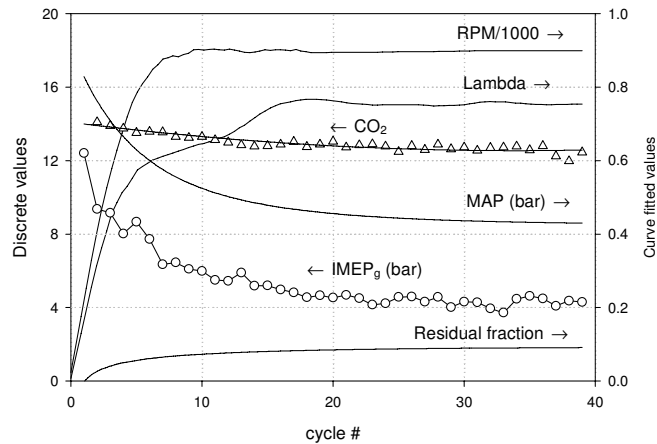


**Figure 3: Baseline engine parameters (not including emission measurements).**

The baseline startup figure also shows the inverse effects of increasing RPM and decreasing MAP and  $IMEP_g$  that is evident for this closed throttle engine start.  $CO_2$ -in post-combustion plateau levels (%) are shown as well as the residual fraction cycle-by-cycle. Since the first engine cycle was not preceded by a combustion event the residual fraction was zero for this first complete engine cycle (the previous day's engine shutdown was always preceded by at least 15 seconds of fuel-off motoring). It should be noted that steady state stabilized engine Wide Open Throttle (WOT) residual burned gas percentages for this CFR engine are nominally 2-3%, while closed throttle residuals are at nominally 10%.

Fuel commanded variations included in this study were at 5% rich, 5% lean, 10% lean and 15% lean from baseline. This final lean case included some engine partial burn and misfiring cycles. Spark variations were performed at the baseline and 5% lean fuel command settings. Modest spark changes with the 5% lean fuel command produced some misfiring cycles, so the baseline fuel setting was used for the spark sweeps later in this paper. Only for very late – retarded spark timings, After Top Center (ATC) were misfiring cycles observed with the baseline (nominally stoichiometric) fueling.

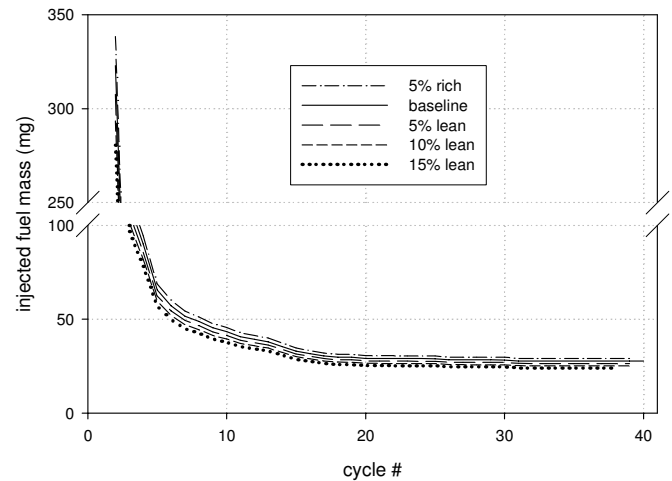


**Figure 4: Injected fuel mass (mg)**

In the following discussions of the experimental data the authors will refer to following 'Phases of Startup' as these three phases produce different behaviors:

**Cranking-Startup Phase:** The first ~6 engine cycles where RPM is rapidly increasing associated with a significant MAP pull down. Significant fueling enleanment from the very rich cranking cycles is commanded.

**Transition Phase:** Engine cycles from ~7-20 where engine speed is nominally constant, however, modest manifold pumping continues (from ~0.6 to 0.4 bar-abs). Modest commanded enleanment is performed.

**Stable Phase:** This phase refers to the stable RPM and MAP period after cycle 20. However, it should be noted that the thermal state of the engine is steadily changing, principally the rapidly increasing intake valve head temperature. In this study fuel pulse width is constant during this stage.

## IN-CYLINDER EQUIVALENCE RATIO DETERMINATION

$CO_2$  in-cylinder data are shown in Figure 5 as a function of cycle number since the start of cranking. This in-cylinder  $CO_2$  data set is composed of the post-main combustion phase  $CO_2$  plateaus reflecting the bulk charge burned gas equivalence ratio. It can be seen that the baseline case provides for the maximum  $CO_2$ -in levels during the first second of engine startup. This is due to the fuel calibration approach used in this paper which adjusted commanded fuel pulse widths in order to maximize  $CO_2$ -in before the parametric study was pursued. Since  $CO_2$  gas concentration in burned gases is maximum for a nominally stoichiometric charge [15], this baseline fueling case is a reflection of an approximately stoichiometric in-cylinder fuel charge throughout the start. It can be seen that  $CO_2$ -in concentration levels are reduced for both rich and lean fuelings from the baseline.