

# Gasoline Fuels Assessment for Delphi's Second Generation Gasoline Direct-Injection Compression Ignition (GDCI) Multi-Cylinder Engine

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## ABSTRACT

Fuel efficiency and emission performance sensitivity to fuel reactivity was examined using Delphi's second-generation Gasoline Direct-Injection Compression Ignition (Gen 2.0 GDCI) multi-cylinder engine. The study was designed to compare a US market gasoline (RON 92 E10) to a higher reactivity gasoline (RON 80) at four operating conditions ranging from light load of 800 rpm / 2.0 bar gross indicated-mean-effective pressure (IMEP<sub>g</sub>) to medium load of 2000 rpm / 10.0 bar IMEP<sub>g</sub>. The experimental assessment indicated that both gasolines could achieve good performance and Tier 3 emission targets at each of the four operating conditions. Relative to the RON 92 E10 gasoline, better fuel consumption and engine-out emissions performance was achieved when using RON 80 gasoline; consistent with our previously reported single-cylinder engine research [1].

More specifically, a fuel consumption improvement was observed at the low load operating conditions (800 rpm / 2.0 bar IMEP<sub>g</sub> and 2000 rpm / 2.6 bar IMEP<sub>g</sub>) when using the RON 80 gasoline, compared to using market RON 92 E10 gasoline mainly due to better combustion stability that is directly associated with the fuel's higher reactivity. For mid-load operation (1500 rpm / 6.0 bar IMEP<sub>g</sub> and 2000 rpm / 10.0 bar IMEP<sub>g</sub>), significantly lower fuel consumption was achieved when using the higher reactivity (RON 80) gasoline due to significantly lower boost pressure requirements and an enhanced combustion process. Clear differences in low temperature heat release (LTHR) behavior for this partially premixed compression ignition (PPCI) combustion process was also observed between the two gasolines.

Specifically for the Delphi Gen 2.0 GDCI multi-cylinder engine, fuel consumption and engine-out emission targets were able to achieve when using both current market RON 92 E10 gasoline and a higher reactivity RON 80 gasoline. Furthermore, the higher reactivity RON 80 gasoline exhibited further improvement of light-to-medium load performance and emissions.

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## INTRODUCTION

Aggressive global fuel economy and criteria pollutant goals continue to drive novel internal combustion engine technologies into the market. The mainstream spark-ignition (SI) gasoline engine utilized in the passenger transportation sector has been effective in meeting low criteria pollutants through maintaining the combustible air-fuel mixture at stoichiometry and utilizing a 3-way aftertreatment system to greatly reduce hydrocarbon (HC), nitrogen oxides (NO<sub>x</sub>), and carbon monoxide (CO) emissions. However, this approach limits the fuel efficiency of the SI engine due to relatively high charge exchange (pumping) losses, relatively low geometric compression ratio, higher heat losses along with non-optimal fluid properties limiting the engines thermodynamic efficiency. On the other hand, the compression-ignition (CI) diesel engine offers excellent fuel efficiency and lower carbon dioxides (CO<sub>2</sub>) emissions compared to

the gasoline SI engine. However, the conventional diesel engine requires modern and relatively expensive aftertreatment technologies to manage the engine-out NO<sub>x</sub> and particulate matter (PM) emissions.

Low temperature combustion (LTC) has becoming a focus of engine research around the world due to its higher thermal efficiency and very low NO<sub>x</sub> and PM emissions and presents an alternative to SI gasoline and CI diesel engines. Homogeneous charge compression ignition (HCCI) is one type of LTC mode. Because HCCI combustion relies on autoignition of a premixed charge, the HCCI ignition timing is decoupled from the fuel injection timing; unlike conventional CI diesel engines, the HCCI combustion process does not have a dominant control parameter to manage the combustion event. Furthermore, the HCCI combustion is very sensitive to thermal condition as well as chemical compositions. HCCI research has evolved from use of very uniform charge mixtures to intentionally

inhomogeneous charge mixtures and temperatures for better controllability of the combustion event [2,3]. The partially premixed compression ignition (PPCI) combustion process implements direct fuel injection with moderate mixing times allowing for a more heterogeneous fuel-air distribution compared to the HCCI combustion process, including both fuel-lean and fuel-rich mixtures. The onset of PPCI combustion is directly coupled to the fuel injection timing compared with HCCI combustion, though chemical kinetics can still have an important role. In addition, the in-cylinder pressure rise rate for PPCI combustion can be controlled through the stratification of charge mixture and temperatures.

Delphi and partners have developed a multi-cylinder engine concept that implements LTC using U.S. market gasoline. In Delphi's Gasoline Direct-Injection Compression Ignition (GDCI) combustion process, fuel is directly injected into the cylinder and partially, but not fully premixed prior to the start of heat release. This engine concept is intended to meet stringent US Tier 3 Bin 30 emission standards with diesel-like fuel efficiency. Preliminary test results of second generation (Gen 2.0) GDCI multi-cylinder engine have been reported; describing a significant improvement in brake-specific fuel consumption (BSFC) over the first generation GDCI engine while meeting targets for engine-out emissions, combustion noise, and stability [4].

PPCI research has been conducted by many researchers around the world using various engine platforms and fuels [5,6,7]. Conventional market gasoline and diesel fuels have been used in many PPCI studies. The results have shown that each fuel has specific advantages and shortcomings for this PPCI mode in terms of operating range, while demonstrating the diesel-like efficiency [8,9,10]. Recent studies have suggested that the optimum fuel for the PPCI mode may have autoignition qualities between those of gasoline and diesel fuel and prefer to have the gasoline range of volatilities [11,12,13]. From these studies, it is apparent that engines that implement PPCI combustion have potential to further improve through optimizing fuel formulations, combustion chamber design, and fuel injection technologies.

In a previous study, the authors characterized four different autoignition quality fuels, ranging from research octane number (RON) 60 through 92, with Delphi's Gen 2.0 GDCI single-cylinder research engine [1]. The study showed that the most reactive fuel (RON 60) performed best at lower load operations and the least reactive fuel (RON 92 E10, US market gasoline) performed best at higher load operations. The study concluded that the RON 80 fuel was able to improve performance and emissions at lower load operations while maintaining similar performance and emissions at higher load operations compared to the RON 92 E10 gasoline with Gen 2.0 GDCI engine hardware configuration.

The objective of this study is to advance the understanding of fuel efficiency and emission performance sensitivity to fuel reactivity with Gen 2.0 GDCI multi-cylinder engine by comparing a US market gasoline (RON 92 E10) to a high reactivity gasoline (RON 80) at four different operating conditions. Thus, further potential to improve

light-to-medium load combustion behavior and to reduce fuel consumption for Gen 2.0 GDCI multi-cylinder engine through optimization of the fuel was investigated in this study.

## ENGINE

The experiments were performed with Gen 2.0 GDCI 1.8-liter multi-cylinder engine. The major engine description will be explained briefly in this section, since the detailed engine description was given by Sellnau et al. [4]. The engine specifications are summarized in Table 1.

The cylinder head, which is rated at 200 bar peak cylinder pressure, has four valves with double overhead camshafts. The injector is centrally-mounted without offset or inclination relative to the cylinder axis. The multi-hole, Gasoline Direct Injection (GDI) injector has a symmetric spray pattern with the intent to minimize piston and liner wetting for all injections. The piston bowl shape was matched to injector spray characteristics and features an open bowl with low surface area for low heat losses. The injection system delivers accurate fuel quantities for multiple injections in the cylinder. The combustion chamber features a shallow with valves flush with the pentroof surface. The low pentroof angle was selected to achieve high compression ratio, while maintaining low surface area and reasonable valve sizes. Intake and exhaust ports were designed for good flow characteristics without swirl, tumble, or squish.

Table 1. Engine specifications [4]

|                          |                                       |
|--------------------------|---------------------------------------|
| Engine Type              | 4-valve Compression Ignition          |
| Displacement             | 1.8 L                                 |
| Bore x Stroke x Rod      | 82.0 x 85.2 x 148.2 mm                |
| Compression ratio        | ~15:1                                 |
| Cylinder Head            | Shallow Pentroof 10 degree            |
| Swirl and Squish         | Minimum Mixture Motion                |
| Piston                   | GDCI Omega                            |
| Oil Jets                 | Enhanced Individual-Cylinder          |
| Cylinder Pressure Rating | 200 bar                               |
| Fuel Injection System    | Central Mount, 400 bar GDI Multi-hole |
| DOHC Type II Valvetrain  | Exhaust Only- Exhaust Rebreathing     |
| Boost System             | 2-Stage (Turbo and Super)             |
| EGR System               | Cooled Low Pressure EGR Loop          |
| Thermal Management       | Low and High Temperature Loops        |
| Aftertreatment           | 2 Gasoline Oxidation Catalysts        |

Full-time GDCI combustion over the full engine operating range is achieved by using exhaust rebreathing at low loads and cooled EGR at medium to higher loads. Exhaust rebreathing is accomplished using the exhaust valve train system, which provides secondary exhaust valve lift event during the intake stroke. It is an effective way to recuperate heat from hot exhaust gases in order to raise mixture temperatures. This heat promotes autoignition at low loads when boost pressure is zero or low. Exhaust rebreathing also reduces pumping work and raises exhaust temperature significantly [14]. In this way, a close-coupled catalyst will remain warm over a wide

range of low loads without special maintenance heating [4]. The exhaust rebreathing functionality is provided by a Type II, continuously variable mechanism valve train system. An electronic variable cam phaser is used to actuate the exhaust valve train and control the secondary valve lift with very fast response.

Intake boosting is difficult when the engine is operating at low load conditions because the exhaust enthalpy to drive a turbocharger is very low. In order to provide the necessary intake boost with low boost parasitics, the intake boost system of the engine includes a variable geometry turbocharger, a supercharger with clutch, and two charge air coolers. No intake throttle is used in this engine.

The low pressure loop exhaust gas recirculation (LP-EGR) system is adopted in this engine. The exhaust gases exit the turbine and pass through a close-coupled oxidation catalyst to reduce HC and CO emissions. The EGR gas feeding line was located between two oxidation catalysts, right after the first oxidation catalyst exit. The EGR system is designed for high flow in a compact layout for fast response on the vehicle.

The aftertreatment system is comprised of only two oxidation catalysts in series. The first oxidation catalyst was close-coupled to the turbocharger outlet for heat conservation. Even though  $\text{NO}_x$  aftertreatment is likely to be needed for stringent US Tier 3 Bin 30 emissions standards, no  $\text{NO}_x$  aftertreatment was used in this Gen 2.0 GDCI engine.

## EXPERIMENTAL SETUP

The experiments were performed on an engine dynamometer at Aramco Research Center – Detroit to characterize the fuel efficiency and emission performance sensitivity to fuel reactivity with the Gen 2.0 GDCI multi-cylinder engine. A 320 kW AC dynamometer was utilized in this study. Engine air flow measurement was taken by an AVL FlowSonix which uses AVL's ultrasonic transit time measurement principle. Fuel flow was measured by an AVL Fuel Exact device using a PLU positive displacement meter and Coriolis type mass flow measurement. Engine coolant temperature, liquid-cooled charge air coolers, and engine oil temperature are controlled using temperature feedback to maintain prescribed set points.

Exhaust emissions were measured by Horiba Mexa-7500DEGR emission bench. A standard heated chemiluminescence detector (CLD) was used for measuring  $\text{NO}_x$  and a flame ionization detector (FID) were used for HC emissions measurement. CO and intake/exhaust  $\text{CO}_2$  emissions were measured using non-dispersive infrared (NDIR) instruments. Paramagnetic detector (PMD) was used to measure  $\text{O}_2$  concentration. Both a smoke meter (AVL 415SE) and a Micro Soot Sensor (AVL 483) were used to measure filter smoke numbers (FSN) and PM concentrations ( $\text{mg}/\text{m}^3$ ) from the raw engine exhaust, respectively.

Flush-mounted Kistler 6125CU20 pressure transducers were used to measure in-cylinder pressure at each cylinder. These transducers were inserted from the top of the cylinder head and located at the

combustion chamber close to the cylinder bore. A Kistler 2614 crankshaft encoder provided crank angle position data with a resolution of  $0.5^\circ$  crank angle. Kistler 5064 charge amplifiers converted the pressure transducer charge into a voltage signal. These in-cylinder pressure signals were referenced thermodynamically using AVL INDICOM software. The combustion noise level was calculated through the build-in combustion noise calculation method in AVL INDICOM.

The engine controller was based on National Instruments hardware and LabView software and was built by National Instruments – San Antonio. The controller features real time combustion analysis using National Instruments Combustion Analysis System (NI-CAS) and allows rapid prototyping of test cell engine control software using LabView. The engine control software for dynamometer testing, developed by Delphi, balances gross indicated mean effective pressure (IMEP<sub>g</sub>) for each cylinder based on in-cylinder pressure data. A multiple-injection-control utility [15] was developed to control the fuel injection quantity for each injection event. The fuel injection quantity for each injection event is determined using instantaneous rail pressure, in-cylinder pressure, and an embedded calibration map for each injector. Fuel rail pressure is tightly controlled using the rail pressure sensor and the GDI fuel pump spill valve. Intake boost is controlled by the supercharger bypass valve and turbocharger rack position for minimum boost parasitic losses. Engine coolant temperature, liquid-cooled charge air coolers, and engine oil temperature are controlled using temperature feedback to maintain prescribed set points. The engine controller provides various other controls functions such as for the EGR valve, supercharger clutch, and 2-stage oil pump.

Throughout this study, the temperatures of oil and coolant into the engine were controlled to maintain at  $90^\circ\text{C}$ . The crank angle location of 5 % fuel mass burned (CA5) and the crank angle location of 50 % fuel mass burned (CA50) were defined as start of combustion (SOC) and combustion phasing, respectively. The crank angle duration from 5 % to 75 % fuel mass burned (CA5-75) was represented combustion duration.

## FUELS

A US market gasoline (RON 92 E10) and a higher reactivity gasoline (RON 80) were investigated in this study in order to characterize the fuel efficiency and emission performance sensitivity to fuel reactivity on the PPCI combustion mode. The RON 92 E10 gasoline, representative of US grade market regular gasoline, has been used for GDCI research for several years [1,4,15,16,17,18]. Based on the results from the previous study performed with Gen 2.0 GDCI single-cylinder research engine, the RON 80 gasoline was chosen and compared with the RON 92 E10 in this study because the RON 80 gasoline exhibited much better performance and emissions behavior at low load conditions while achieving similar performance and emissions behavior at higher load engine operation compared to the RON 92 E10 gasoline [1]. The major fuel properties are listed in Table 2. As shown in the table, the RON 80 gasoline has higher heating value and specific gravity compared to the RON 92 E10 gasoline.

Table 2. Fuel properties of tested fuels [1]

| Fuel                         | RON 92 E10 | RON 80 |
|------------------------------|------------|--------|
| Research Octane Number       | 92.6       | 80.3   |
| Motor Octane Number          | 83.0       | 77.9   |
| Derived Cetane Number        | 21.0       | 26.3   |
| Specific Gravity at 15.56 °C | 0.720      | 0.745  |
| Gross Heating Value [MJ/kg]  | 45.08      | 46.76  |
| Net Heating Value [MJ/kg]    | 42.09      | 43.68  |
| Carbon [wt%]                 | 81.90      | 85.49  |
| Hydrogen [wt%]               | 14.07      | 14.51  |
| Oxygen [wt%]                 | 4.03       | 0.00   |

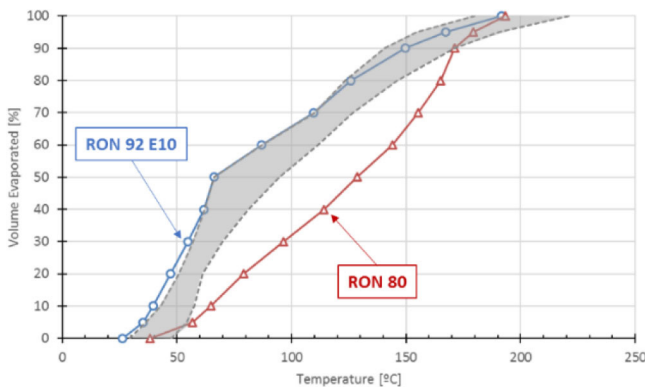


Figure 1. Distillation characteristics of tested fuels [1]

Figure 1 shows the distillation characteristics of two tested fuels. The dotted grey area in the figure represents the distillation range of typical US market gasolines [19]. The RON 92 E10 gasoline used in this study was at the lighter end of the distillation range of typical US market gasolines because this fuel was procured during the winter season. The RON 80 gasoline showed similar initial and final boiling temperatures as the RON 92 E10 gasoline. Even though the RON 80 gasoline showed less volatility throughout the distillation curve than the RON 92 E10 gasoline, the distillation ranges for both fuels are within typical gasoline range.

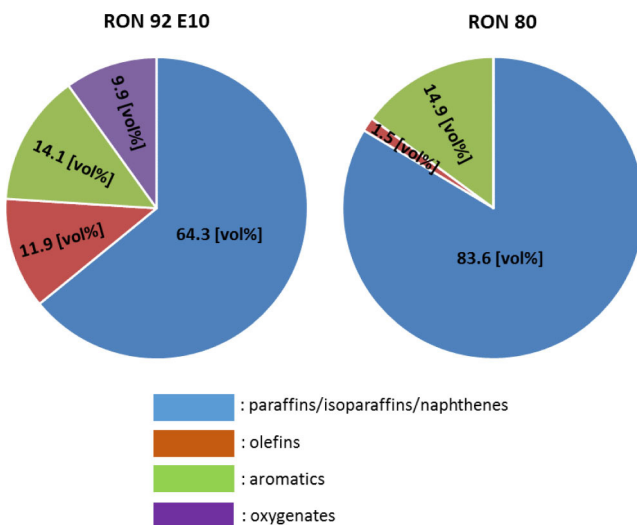


Figure 2. Chemical compositions of tested fuels

The analysis of fuels' chemical compositions was performed by using Fluorescent Indicator Adsorption (FIA) method [20]. The results of two tested fuels were compared in Figure 2. The RON 80 gasoline shows higher concentration of the saturated compositions (such as paraffins, isoparaffins, and naphthenes) than the RON 92 E10, that is, the RON 80 gasoline is consisted of mostly paraffinic components. Both fuels contained similar level of aromatic contents while much lower olefins concentration was observed in the RON 80 fuel.

## ENGINE OPERATING CONDITIONS

The Gen 2.0 GDCI multi-cylinder engine was tested on a steady-state dynamometer at four engine operating conditions covering from light load to medium load range. The engine was optimized by manually adjusting various control parameters. Table 3 lists the four engine operating conditions focused in this study. At the lowest load conditions, 800 rpm / 2.0 bar gross indicated mean effective pressure (IMEP<sub>g</sub>) and 2000 rpm / ~2.6 bar IMEP<sub>g</sub> (equivalent to 2.0 bar brake mean effective pressure (BMEP)), intake boost was not required for both fuels and the engine was able to operate at naturally aspirated (NA) condition with the supercharger declutched. Exhaust rebreathing strategy was applied for three low load engine operating conditions, 800 rpm / 2.0 bar IMEP<sub>g</sub>, 2000 rpm / ~2.6 bar IMEP<sub>g</sub>, and 1500 rpm / 6.0 bar IMEP<sub>g</sub>. However, only cooled external EGR was used for 2000 rpm / 10.0 bar IMEP<sub>g</sub> engine operation.

Table 3. Engine operating conditions

| Engine Speed | Load                       | Description                               |
|--------------|----------------------------|-------------------------------------------|
| 800 rpm      | 2.0 bar IMEP <sub>g</sub>  | Idle condition                            |
| 2000 rpm     | ~2.6 bar IMEP <sub>g</sub> | Global point (equivalent to 2.0 bar BMEP) |
| 1500 rpm     | 6.0 bar IMEP <sub>g</sub>  | Low load condition                        |
| 2000 rpm     | 10.0 bar IMEP <sub>g</sub> | Medium load condition                     |

Preliminary targets for engine-out emissions, combustion stability, and combustion noise level (CNL) for this study are shown in Table 4. It is expected that the targets, especially engine-out emissions, will continue to evolve as the PPCI combustion strategy is further optimized and better engineering solutions become available for the aftertreatment system.

Table 4. Preliminary targets for engine testing [1,3]

| Engine Speed [rpm]                                   | 800   | 2000 | 1500 | 2000 |
|------------------------------------------------------|-------|------|------|------|
| Load (IMEP <sub>g</sub> ) [bar]                      | 2.0   | ~2.6 | 6.0  | 10.0 |
| Engine-out (ISNO <sub>x</sub> ) <sub>g</sub> [g/kWh] | ≤ 0.2 |      |      |      |
| Engine-out Smoke [FSN]                               | ≤ 0.1 |      |      |      |
| COV IMEP <sub>g</sub> [%]                            | ≤ 3.0 |      |      |      |
| CNL [dB]                                             | ≤ 72  | ≤ 83 | ≤ 86 | ≤ 93 |

## RESULTS AND DISCUSSION

The fuel sensitivity of engine performance and emissions was evaluated at four engine operating conditions for both RON 92 E10 and RON 80 gasolines. The engine operating conditions discussed in this section are optimized results based on several engine test