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Maximizing the benefits of high octane fuels in spark-ignition engines

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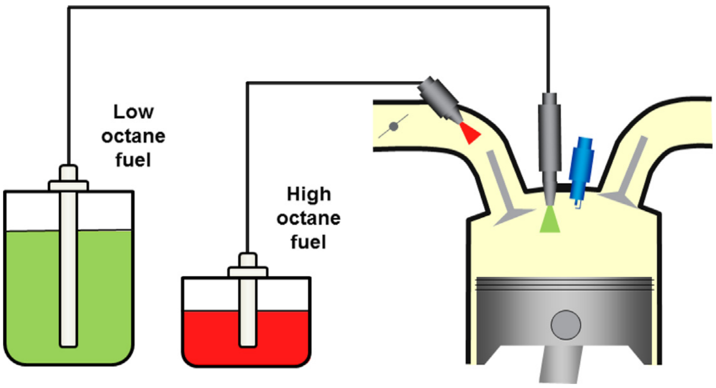
HIGHLIGHTS

- Octane-on-Demand was compared with two gasolines containing ethanol (E10 and E30).
- Specific fuel consumption was reduced by up to 10% with respect to the E30 gasoline.
- Methanol was more effective at suppressing knock than ethanol.
- Efficiency and specific fuel consumption can be decoupled in dual-fuel engines.
- Minimizing specific fuel consumption marginally increased the specific CO_2 emissions.

GRAPHICAL ABSTRACT

Schematic of the Octane-on-Demand dual injection system fitted to the engine.



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ABSTRACT

Higher octane gasoline will be an important factor in enabling future spark-ignition engines to meet increasingly stringent fuel economy and CO_2 emissions requirements. The most effective method to raise the octane 'floor' of regular grade gasoline is through the use high octane blend components, such as methanol and ethanol. However, this is often limited by the negative effects associated with energy density, phase separation and cold engine starting. This paper therefore examines the optimal way to leverage the most widely available high octane fuels to improve the performance and environmental impact of light-duty vehicles. A comprehensive set of baseline engine data is first presented for two splash-blended gasolines containing ethanol (E10 and E30). The octane quality of these fuels (RON 93 and 101) has been raised by directly displacing the gasoline blendstock (RON 90) with higher octane ethanol (RON ~109). The two splash-blended gasolines are compared with the Octane-on-Demand concept, which instead leverages only the necessary amount of high octane fuel when the octane requirement of the engine exceeds the level that can be provided by the oil-derived base fuel. The same gasoline blendstock is used in both cases, thus enabling the leveraging effect of the high octane fuels in the Octane-on-Demand configuration to be directly quantified. The results demonstrate that the Octane-on-Demand concept used in

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Abbreviations: aTDC, After top dead center; BOB, Blendstock for oxygenate blending; bTDC, Before top dead center; CA50, Crank angle at which 50% of the fuel mass has been burned; CAD, Crank angle degrees; cc, Cubic centimeters; CoV, Coefficient of variation; CO_2, Carbon dioxide; CR, Compression ratio; DHA, Detailed hydrocarbon analysis; DI, Direct injection; E10, Fuel containing up to 10% ethanol by volume; E30, Fuel containing up to 30% ethanol by volume; EtOH, Ethanol; EVC, Exhaust valve closing; EVO, Exhaust valve opening; EGR, Exhaust Gas Recirculation; H/C, Molar hydrogen-to-carbon ratio; HoV, Heat of vaporization; IMEP, Indicated mean effective pressure; IVC, Intake valve closing; IVO, Intake valve opening; KI, Knock intensity; LHV, Lower heating value; MeOH, Methanol; MBT, Minimum spark advance for best torque; Min. FC, Minimum combined fuel consumption; MON, Motor octane number; NMEP, Net mean effective pressure; $NSCO_2$, Net specific carbon dioxide emissions; NSFC, Net specific fuel consumption; OoD, Octane-on-Demand; PCP, Peak cylinder pressure; PE, Peak efficiency; PFI, Port-fuel injection; RON, Research octane number; rpm, Revolutions per minute; RVP, Reid Vapor Pressure; SCRE, Single cylinder research engine; SG, Specific gravity; SOI, Start of injection; TCO, Total cost of ownership; VVT, Variable valve timing; % mol/mol, Mole fraction; % v/v, Volume fraction; % w/w, Weight fraction; σ, Standard deviation.

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conjunction with either methanol or ethanol provides comparable or lower specific CO_2 emissions to the E30 gasoline, with up to a 10% improvement in specific fuel consumption. The use of a non-traditional engine calibration strategy that maximizes the trade-off between thermal efficiency and fuel energy density also enables the amount of high octane fuel required to suppress knock to be reduced by at least 25%, with methanol offering the greatest benefits. This however comes at the expense of marginally higher specific CO_2 emissions than could otherwise be achieved. Overall, this work suggests that powertrains designed around the Octane-on-Demand concept may provide greater social and environmental benefits than those designed for high octane splash-blended gasolines with significant methanol or ethanol content.

1. Introduction

Spark-ignition engines are an attractive candidate for additional investment to improve efficiency and reduce CO_2 emissions. This established technology platform offers cost advantages over competing mobility technologies, while requiring far less complex fuel delivery and exhaust aftertreatment systems than modern diesel engines. Spark-ignition engines also offer a unique synergy with a range of low cost technologies that can reduce the traditional losses encountered at both low and high engine loads. Examples of these include cylinder deactivation systems, cooled exhaust gas recirculation (EGR), hybridization and water injection systems [1–4].

The widespread adoption of smaller displacement turbocharged engines has been a further driver of efficiency gains in light-duty vehicles. The production share of these engines in the United States grew fivefold between 2009 and 2014 [5]. This trend is expected to continue, with some projections indicating that light-duty vehicles equipped with turbocharged engines will account for 83% of sales by 2025 [6]. Turbocharging is generally combined with direct fuel injection and variable valve timing (VVT) to increase the specific output of the engine. This allows taller transmission ratios to be used, thereby shifting the region of engine operation to lower speeds and higher loads where parasitic losses are considerably lower.

However, higher specific output engines also experience more extreme in-cylinder pressure and temperature conditions. This increases the susceptibility of the engine to abnormal combustion phenomena such as preignition, knock and superknock [7–9]. It also causes the performance, fuel economy and exhaust emissions of such engines to be significantly degraded if the fuel octane quality is below the intended level [10,11]. For these reasons, there is general consensus that the octane quality of regular grade gasoline is no longer adequate to enable advanced spark-ignition engines to meet increasingly stringent fuel economy and CO_2 emissions requirements [12–14].

Regular grade gasoline currently accounts for around 85% to 90% of sales volumes in most countries [6,15]. In Europe, the EN 228 standard [16] requires regular grade gasoline to have minimum Research and Motor octane numbers (RON and MON) of 95 and 85 respectively. This standard also imposes specific limits on the use of high octane blend components such as methanol and ethanol (3.0% and 5.0% v/v respectively). The octane quality of European gasoline is typically two to four units higher than the equivalent regular grade gasoline in countries such as the United States and Australia, despite nearly all gasolines in these regions containing 10% v/v ethanol [17].

Raising the octane ‘floor’ of regular grade gasoline at the refinery level could be achieved using several approaches. This could involve greater use of *n*-butane, which is a low value component that offers comparatively high octane quality [18–20]. However, the gasoline Reid Vapor Pressure (RVP) requirement limits its use, particularly in warmer climates. Further refinery octane addition would therefore likely depend upon displacing the lower octane straight-run streams in the gasoline pool with much higher value and energy intensive streams from the alkylation, catalytic reforming and/or isomerization units. However, this would lead to reduced gasoline yields and create a surplus of hydrocarbons in the gasoline boiling range [21]. It may also require significant investment in refinery infrastructure on a global scale [22].

High octane gasolines containing mid-levels of ethanol or methanol have therefore been widely promoted as the most effective means of raising the octane floor of regular grade gasoline [23–27]. Ethanol and methanol have high octane numbers (RON ~109) and latent heats of vaporization (HoV) that are between four and seven times greater than regular gasolines on a stoichiometric basis. These properties generally enhance the practical anti-knock quality of conventional liquid fuels, even in relatively small concentrations [28–30]. This enables higher thermal efficiencies to be achieved from engines that have been optimized to exploit the superior fuel anti-knock quality. Nevertheless, volumetric fuel economy parity with existing market gasolines has so far been difficult to achieve, due to the lower energy density of fuels with significant methanol or ethanol content [31–34].

Rather than directly displacing gasoline with methanol or ethanol, an improved approach would involve leveraging a limited amount of high octane fuel to enable the engine to be more efficient in its use of an oil-derived fuel, which has considerably higher energy density. The oil-derived fuel would be used at low and intermediate loads where energy density is generally more important than octane quality, while the high octane fuel would only be used at higher loads to suppress knock. This so-called *Octane-on-Demand* concept therefore combines the high energy density and widespread availability of oil-derived fuels with the superior octane quality of methanol or ethanol, while minimizing the negative effects associated with energy density, phase separation and cold engine starting [35,36].

The basic Octane-on-Demand concept was described as early as the 1940s [37]. This system enabled vehicles to operate infrequently at high severity conditions, while still utilizing the comparatively low octane quality gasolines of the day for almost all urban driving. This eliminated octane giveaway, and reduced the burden on early refiners to produce large quantities of high octane gasoline. Renewed interest in the Octane-on-Demand concept in recent years can mainly be attributed to the need to increase engine efficiency [38,39]. This can be achieved by exploiting the improved high load performance provided by the Octane-on-Demand concept to increase the use of engine boosting and higher compression ratios [40–42]. These efficiency benefits can often be realized in combination with reductions in both gaseous and particulate emissions, particularly when methanol or ethanol are utilized as high octane fuels [43–45]. Several automakers are also