

Onboard Gasoline Separation for Improved Vehicle Efficiency

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ABSTRACT

ExxonMobil, Corning and Toyota have collaborated on an Onboard Separation System (OBS) to improve gasoline engine efficiency and performance. OBS is a membrane based process that separates gasoline into higher and lower octane fractions, allowing optimal use of fuel components based on engine requirements. The novel polymer-ceramic composite monolith membrane has been demonstrated to be stable to E10 gasoline, while typically providing 20% yield of ~100 RON product when using RUL 92 RON gasoline. The OBS system makes use of wasted exhaust energy to effect the fuel separation and provides a simple and reliable means for managing the separated fuels that has been demonstrated using several generations of dual fuel test vehicles. Potential applications include downsizing to increase fuel economy by ~10% while maintaining performance, and with turbocharging to improve knock resistance.

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INTRODUCTION

Nearly all vehicles sold today specify a single fuel. For spark ignition gasoline engines the fuels are specified based on octane rating. Several fuel grades are available: In the U.S., regular or RUL typically has a pump octane rating of 87 AKI (~92 RON) and premium or PUL has a pump octane rating of 93 AKI (~97 RON), with several intermediate grades available.

Most vehicles sold today specify regular gasoline. A smaller number of high performance and luxury vehicles specify premium gasoline, and generally have higher compression ratio engines.

Increasing compression ratio has long been recognized as an effective means of improving combustion efficiency, but historically has been knock limited by the octane rating of the fuel used (1). Advances in automotive computer control of spark timing, fuel injection (both port and direct), control of air-fuel ratio, variable valve timing and cool exhaust gas recirculation, have allowed substantial increases in effective compression ratio, while allowing the use of regular ~92 RON gasoline without knock (2). In some cases the use of premium

gasoline can improve peak performance, but at an added cost to the consumer, and with little effect on fuel economy, if the engine is designed to operate on regular gasoline.

Gasoline itself is a complex mixture of hydrocarbons, oxygenates and additives with a range of physical and chemical properties. The composition can vary widely. In Japan for example, there are no oxygenates and the higher octane components are typically aromatic hydrocarbons of about 105-115 RON. Aromatic levels of 25-30 vol.% are typical. In the United States, the oxygenate ethanol is presently at the 10 vol.% level, with higher levels envisioned. Ethanol has an octane rating of about 109 RON, allowing lower octane hydrocarbons blends to be used to meet the required market fuel octane rating. Non-alkylate, aliphatic hydrocarbons in gasoline average about 83 RON. The more volatile light hydrocarbons can have RONs approaching 100 (iso-pentane RON = 92), while the higher boiling aliphatics can have RONs that can be much lower (n-heptane RON = 0).

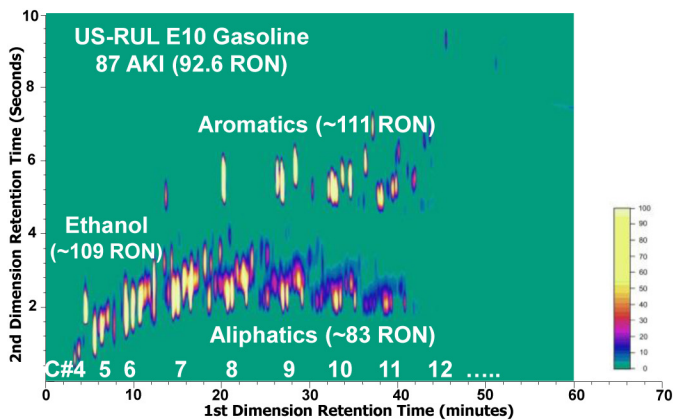


Figure 1. Gasoline composition. 2-D GC of US RUL Gasoline.

Figure 1 illustrates the compositional complexity of a U.S. RUL gasoline by 2-D GC (3). The 2D-GC technique separates components in the gasoline by boiling point (1st dimension) and polarity (2nd dimension). Gasoline is a complex mixture of C₄-C₁₂ hydrocarbons and ethanol blended to obtain required octane number (to prevent engine knock) and volatility (for cold start). Additives, including antioxidants, metal inhibitors, and detergents, are used to improve fuel stability and engine cleanliness. Premium gasoline typically also includes highly branched paraffinic alkylate (isooctane), but supplies are limited by refining capacity and cost.

The effect of fuel octane number and composition on engine performance in a high compression ratio, spark ignition, direct injection (CR13, SIDI) test engine was studied in a collaborative effort by ExxonMobil and Toyota (4). Under low load, low speed stratified conditions it was found that a very low octane, 84 RON, aliphatic fuel resulted in higher efficiency and lower hydrocarbons than obtained with regular 92 RON gasoline. Spark induced compression ignition (SICI) was evident with the very low RON fuel. Furthermore, studies at wide open throttle conditions indicated that a higher octane, highly aromatic fuel (RON 103, 60% toluene) provided significant torque benefits compared to pure isooctane (RON=100) greater than expected based on RON alone.

Octane Requirement Map

Subsequent engine tests, using the same 2 liter 13CR SIDI described (4), under both stratified, lean burn conditions, and homogeneous stoichiometric conditions, using a variety of fuel compositions with RON from 84 to 103, at several load points were made confirming these results. From these data an "Octane Requirement Map" was developed. Lower RON fuels gave higher brake efficiency at low loads in stratified operation. At intermediate loads and stoichiometric operation, maximum efficiency was obtained with the intermediate RON fuels. At higher loads and stoichiometric operation the higher RON fuels gave the best efficiency and were required to avoid knock. Spark advance for each fuel was set by trace knock limit (TKL).

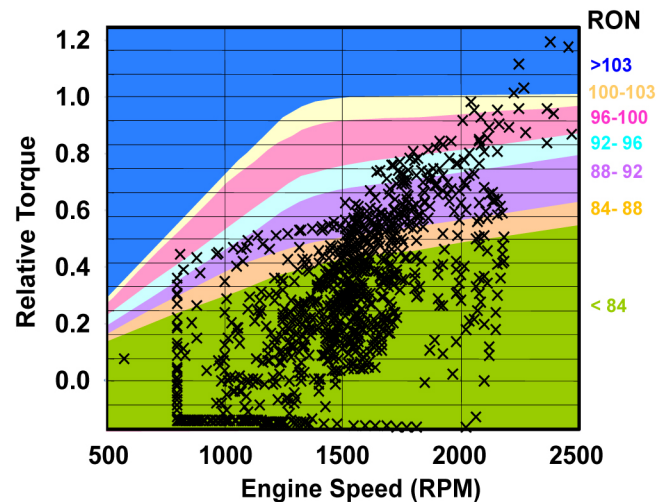


Figure 2. Octane Requirement Map for LA-4 Drive Cycle

The optimal conditions and fuel required for each operating point in the LA-4 drive cycle was determined using the assumption of switching point on mode map, as shown in Figure 2. LA-4 is the EPA Urban Dynamometer Driving Schedule, or UDSS, which represents city driving conditions (22). The total quantity of each RON fuel was then determined by integrating fuel use over the cycle. The relative percentage of each shown in the "pie chart" as Figure 3 shows that optimal engine efficiency requires only modest amounts of >96 high RON fuel, even with 13:1 CR. Most of the drive cycle required <92 RON fuel for optimal efficiency. The results suggest that <84 RON fuel may be acceptable under some low load conditions, but 84 RON was lowest RON tested.

The "Optimal RON Map" fuel requirements for the LA-4 cycle using the SIDI 13:1 high compression engine data just described were used to estimate potential fuel economy credits.

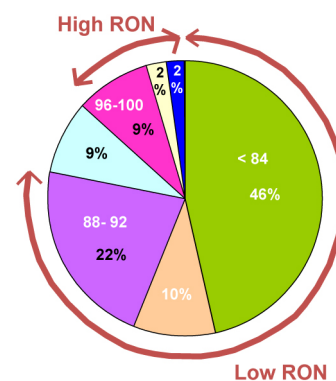


Figure 3. RON Distribution required for LA-4 Drive Cycle.

Fuel economy credits were estimated to be 8.5% by using the optimal fuel octane throughout the LA-4 drive cycle. The 13% increase in torque available with 13:1 CR engine operated on the highest octane fuel allows for a reduction in displacement resulting and in another 7% potential improvement in fuel economy while maintaining constant performance. All totaled, potentially a 15.5% increase in fuel economy. Some of the fuel economy benefit came from the higher compression ratio.

of 13:1, compared to the base compression ratio of 9.8:1; and half from the torque increase, thereby allowing a smaller displacement engine or higher gearing.

These results were intriguing. This “Octane Requirement Map” indicated that nearly 80% of the fuel requirement using a very high compression engine might be met with conventional regular gasoline having RON 92 or less. When under load, about 20% premium gasoline of RON 97 or greater would be required for optimal performance. Notably, even with premium fuel it would not be possible to reach MBT under all conditions at 13 compression ratio. However, concentrating the higher octane components in gasoline, such as aromatics and/or ethanol (in some markets), might provide the higher RON and ignition characteristics required.

This suggested potential for a dual (or multi) fuel strategy to realize significant efficiency and emissions benefits. Recognizing the difficulties of providing multiple fuels to a vehicle, and the desirability of providing a higher RON fuel than commonly available, the thought of separating gasoline onboard was raised.

CONCEPT OF HIGH COMPRESSION ENGINE WITH ONBOARD SEPARATION SYSTEM

The Onboard separation concept arose from the fundamental combustion research jointly conducted by ExxonMobil and Toyota (4). From these studies we learned that aromatics have higher knock resistance than other molecules at the same octane. The high octane fuels used in the studies described above to establish the Octane Requirement Map had high percentages of aromatics' e.g. 60% vol.% at 103.

Recognizing that aromatics are among the highest octane components present in all gasoline, we developed the concept of separating the gasoline into high and low octane fuels onboard a vehicle by means of a pervaporation membrane process (5). Using engineering models for ExxonMobil's proprietary aromatic selective membranes (6, 7), we found that conceptually an onboard system could be developed to provide about 20% yield of 100 RON (research octane number) from typical 92 RON regular gasoline.

Onboard Separation

Onboard separation, or OBS, is a membrane based process that separates gasoline into higher and lower octane fractions, allowing optimal use of fuel components based on engine requirements. The conceptual scheme is shown in Figure 4.

When regular grade gasoline of about 92 RON is separated, two fuels are produced. The higher octane fraction can reach about 100 RON, while the corresponding lower octane fraction is typically 90 RON, or less, depending on yield. About 20%

yield of the higher octane fuel can be obtained with most regular gasolines. Both yield and octane can vary with gasoline composition and fuel demand.

The availability of about 100 RON fuel enables the efficient use of a higher engine compression ratio thereby improving engine efficiency and torque. Each fuel is provided to the engine as required to obtain optimal performance.

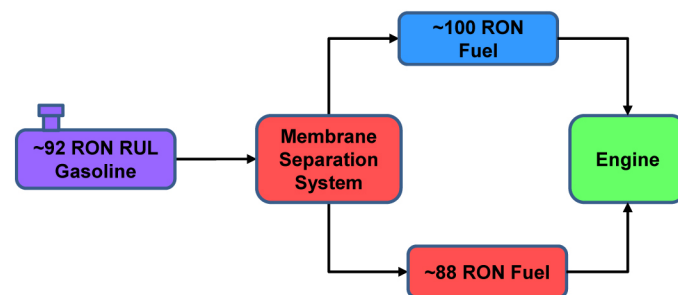


Figure 4. Onboard Separation Concept

Fuel Compositions

Typical regular unleaded gasolines were used for most vehicle, membrane and OBS system evaluations. Japan RUL gasolines having about 90 RON were sourced from a Japanese refinery. Typical aromatic contents were 25-30 vol.%, depending on season sampled. U.S. RUL E10 gasoline having 87 AKI (92 RON) was obtained from a U.S. East Coast terminal. Additional properties and compositions of these fuels are provided in tables that follow.

Ethanol was also splash blended at 10 vol.% with the Japan RUL for membrane lifetime and performance testing. This increased the octane number from 90 to about 93 RON.

Several fuel blends were prepared to simulate the separated fuels. The blend compositions were based on both laboratory membrane separations of gasoline and engineering models of the membrane system. Fuels were blended from refinery products to simulate separated fuel compositions and properties. Fuel properties are shown in Table 1. These fuels were used for initial dual fuel engine bench tests and tuning of the test vehicles.

Table 1. Fuel Properties for Bench Tests

Fuel	W-RUL	Lo RON	Mid RON	Hi RON	Max RON
RON	91.7	89.4	96.6	99.3	101.8
MON	82.7	81.3	85.6	87.7	91.3
AKI	87.2	85.4	91.1	93.5	96.6
Aromatics, wt%	32.2	24.9	59.3	68.6	78.0
LHV kJ/g	43.2	43.4	42.2	42.0	41.6
RVP kPa	92	87.8	36.1	30.2	23.0
T10 %vol, C	51	41	77	84	99
T50 %vol, C	101	88	120	126	129
T90 %vol, C	157	139	159	162	163

The base winter grade fuel W-RUL had RON 91.7 and RVP 42 kPa with aromatic content of 32 wt.%. The LoRON fuel blend RON was 89.4 with RVP 88kPa and aromatic content of 24.9%. Several HiRON blends were made with octane numbers of about 97 to 102, with increased aromatic contents from 59 to 78 wt.%. All HiRON blends had lower vapor pressures consistent with the actually separated fuels. The HiRON blend at 99 RON was similar to actually separated fuel.

Dual Fuel Engine with DI and PFI

Toyota D-4(S) 1AZ-FSE 2L engines were modified, increasing compression ratio from 9.8 to 13:1, while maintaining Direct Fuel Injection (DFI) for the lower octane fuels, and adding Port Fuel Injection (PFI) for the high octane fuel to evaluate dual fuel operation on both the test bench and in the OBS test vehicles, as shown in Figure 5.

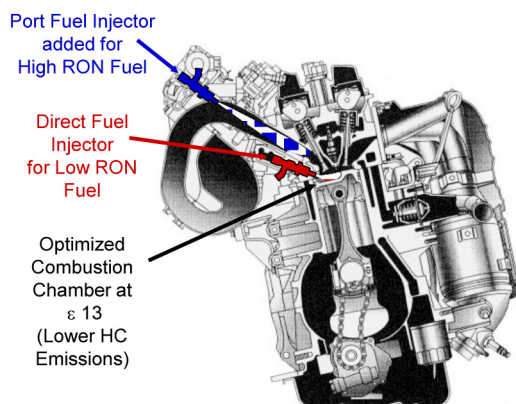


Figure 5. Dual Fuel DI+PFI SI Engine, based on 1AZ-FSE.

This injector configuration was used to minimize fouling of the direct injectors, while providing adequate performance with HiRON fuel when under load and stoichiometric to rich conditions. The system is similar to that described for the dual injector 2GR-FSE engine (14).

The original deep cavity pistons designed for stratified charge applications were replaced with shallow cavity pistons as used in the stoichiometric D-4S (13), with an aim for lower HC emissions. Variable valve timing was not used. Specifications are provided in Table 2.

Table 2. Specifications for a modified engine, with both direct and port fuel injection.

Displacement	1998 cc
Compression Ratio	13.0:1
Bore * Stroke	86 * 86 mm
Valve Mechanism (fixed timing)	16-valve DOHC, Chain Drive
Direct Injection	D4 Fan Spray Injector at 12 MPa
Port Injection	PFI- Multi at 400-500 kPa

Wide open throttle (WOT) testing of this dual fuel engine on the dynamometer confirmed the expected improvements in torque and fuel consumption on increasing compression ratio from 9.8

to 13:1 when using the higher octane fuels and port fuel injection, as shown in Figure 6. Torque was up 12% and achieved MBT at all engine speeds with the nominal 103 RON fuel (actually MaxRON =102 RON). Fuel consumption (BSFC) decreased by about 10% at 4000 rpm.

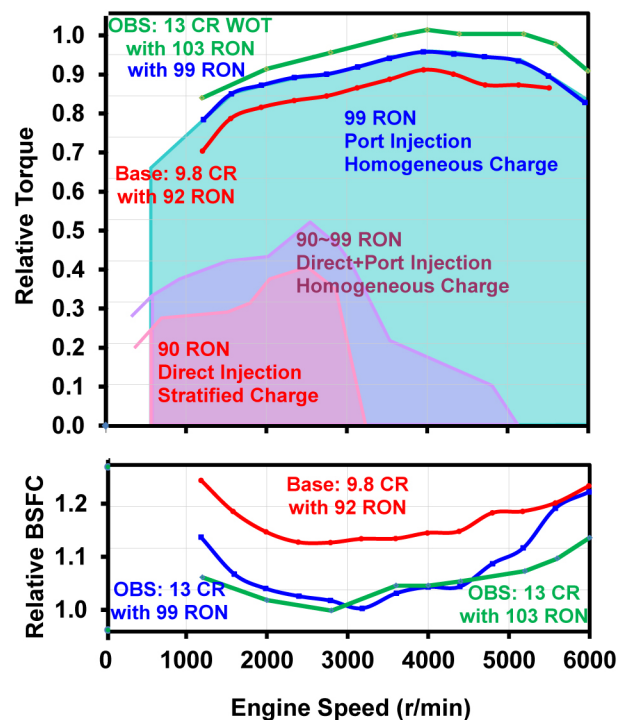


Figure 6. Dual Fuel 13CR Engine Test at WOT

At 99 RON, torque was up about 5% at the TKL and did not achieve MBT spark timing. Although not at MBT spark timing, fuel consumption improvement was comparable to that achieved with the higher octane fuel, except at the highest engine speeds.

Figure 6 also indicates the regions of the engine map corresponding to use of direct injection with stratified fuel charge at low load using lower octane fuels, the transition region where both direct and port injection are used to meet intermediate octane requirements, and the homogeneous port injection region using high octane fuel at higher loads.

SICI combustion was not apparent with the 88-90 RON low octane fuels actually separated, thereby limiting the effectiveness of the stratified charge approach originally envisioned (4). The engines were therefore operated stoichiometrically, after the initial trials.

Drive Cycle Octane Requirements

A simplified Octane Requirement Map, shown in Figure 7 and similar to that shown in Figure 2, was used to estimate drive cycle octane requirements based on load and engine speed required at 13 CR. In emission evaluation mode, HiRON requirement is less than 20%. In high speed, high load cycles the optimal HiRON requirement can be more than 40%.