Meeting the Time-Varying Gasoline Engine’s Octane Requirement Through On-Board Fuel Blending

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2nd CRC Advanced Fuel and Efficiency Workshop
Livermore, CA; November 1-3, 2016
Octane-On-Demand: Background

1. Only at higher engine torque/bmep is the fuel’s octane number (RON) actually needed to suppress knock.
2. The fuel’s octane rating limits the compression ratio and turbocharger boost levels the engine can use.
3. Most countries use “one size fits all” re octane rating of the standard fuel produced and supplied.
4. Can we implement Octane-on-demand: use on-board fuel blending to match the octane rating of fuel supplied to engine to the engine’s actual fuel octane requirement?
5. What are the potential benefits of this approach?
Ways to Improve Efficiency through Octane Management

1. Raise the octane rating of the standard gasoline (US regular, now 92 RON) to higher level (e.g., to 98 RON, current premium).

2. Use two fuel tanks on the vehicle: a smaller one for the higher RON fuel; a larger one for lower RON fuel. Appropriately blend these two fuels to meet the engine’s time-varying octane requirement.

3. One approach: external fill for each tank; smaller tank is sized for much less frequent fill.

4. Another approach: use an on-board fuel separator to separate the standard fuel (put into the main tank) into the higher octane and lower octane fuel streams.

5. Ethanol would be key gasoline component in all of these.
**Turbocharged Gasoline Engine Performance Map: Brake Efficiency Data**

Right: Turbocharged gasoline engine performance map

Left: Fuel conversion efficiency as function of engine load at 2000 rev/min for this TC engine: stoichiometric operation, optimum spark timing.

Source: Young Jo, Raymond Lewis, SAE 2014-01-1206
Average Relative Efficiency (Weighted and Normalized)

Results at constant engine displacement:

$r_c$ increases 10 to 12, $\Delta \eta_{f,b} = 3.8\%$; 12 to 14, $\Delta \eta_{f,b} = 2.1\%$

(Source: Patrick Smith et al., SAE paper 2014-01-2599).
Blending Ethanol with Gasoline to Improve Octane

Higher-Octane Gasoline Study: MIT

- Higher octane regular was examined: 98 RON, 100 RON

- Literature: 4 – 6 higher RON per unit $r_c$ increase; so $r_c$ increase is 1.5 – 1.0 for 98 RON

- Fuel consumption decrease: 3 – 4.5% naturally-aspirated gasoline engines; turbocharged, 1.65 times these values

- Fuel and engine changes initiated in 2020: new, higher $r_c$ engine, NA-SI, TC-SI, hybrid, vehicle deployment starts

- Modeling of refinery impacts indicates that up to 98 RON high-octane standard gasoline (with 10 – 15% ethanol blend) additional energy is not significant (see Speth, R.L., Environ. Sci. Technol., 48, 6561-6568, 2014)
Projected U.S. in-use fleet fuel consumption reduction of up to 5% by 2040. 80% of fuel is then 98 RON. Benefit is up to 7% by 2050.

Octane-On-Demand Approaches

Externally Filled Tanks
- Two separate tanks: one for regular gasoline, one for E85 (85% ethanol + 15% gasoline)
- High octane fuel obtained by refueling the second tank

On-board Separation
- Separate tank for high octane fuel
- High octane fuel obtained by membrane separation system
- Separation process requires additional power, takes time

Octane-on-Demand: Matching fuels to engine needs

1. Example of turbocharged engine octane requirement as function of load.

2. Average RON to avoid knock is 63, 56, and 83 for Urban, Highway, US06 Drive Cycles.

3. On-board separation of high-octane fuel components enables this opportunity

Jo, Bromberg, Heywood, DOE project: SAE 2016-01-0786, 2016-01-0831.

PRF Octane Requirements of the 2-liter Turbocharged Engine vs. BMEP (load), at MBT spark timing. Dr. Young Suk Jo.
Octane Requirements of a TC Engine

RON Requirement Map

- 0 RON fuel limit at around 2 bar BMEP
- 102 RON fuel (about 30% ethanol added to 91 RON gasoline) is good enough until ~19 bar BMEP
- Rate of octane-requirement increase is substantial in low load range
- Above peak pressure limited BMEP, spark retard is necessary
On-Board Fuel Separation

Honda System

Ethanol Concentration “Target” Over 60%

Feed E10 Gasoline
Membrane Pore-flow Model

Pervaporation Process

- Saturation pressure and partial vapor pressure drives the process
- Constant B (pore size, Henry’s constant, adsorption layer thickness)

\[ B_{Pore} = \frac{\pi \cdot (2 \cdot r_{Pore} \cdot l_{Ad} - l_{Ad}^2) \cdot l_{Ad} \cdot N_t \cdot R \cdot T}{8 \cdot r_{Pore} \cdot \mu_i} \left( k'_{D,i} \right)^2 \]

\[ J_i = \frac{B_{Pore}^i}{l_M} \left( (p_{i}^{sat})^2 - (p_{i}^{vapour})^2 \right) \]

\[ J_j = \frac{B_{Pore}^j}{l_M} \left( (p_{j}^{sat})^2 - (p_{j}^{vapour})^2 \right) \]

Figure 5. Pore flow model ($p_{vapour}^{sat} > p_{i}^{sat}$) (after [150]).

Okada, Matsuura, Predictability of transport equations for pervaporation on the basis of pore-flow mechanism
Two-Tank System (Passenger Vehicle)

**TC effects (at MBT)**
- Gallons per 1000 miles of driving
- Fuel consumption decreases with increasing boost and downsizing
- **Note lower volumetric energy content** of ethanol (about 2/3 that of gasoline)
- Benefits: US Combined cycle—20% mpg gain; US06 cycle—15% mpg gain; 50% downsizing

**Leveraging Effects**
- Each gallon of ethanol used replaces, and displaces gasoline
- 1 gallon of E85 replaces **9.8 gallons of gasoline** for 30% TC in US06 cycle (reduces to 1.5 gallons for 50% TC case)
Spark retard effects (at 50% downsizing)

- Up to 5 CAD spark retard, total fuel consumption increases modestly: up to 10 CAD retard, more significant increase
- Overall, up to 5 CAD retard is sensible balance between increasing the fuel consumption and decreasing ethanol use
On-Board Separation System Behavior

**Full Tank Scenario**
- 50% downsized engine, 9.2:1 CR
- 15 gallons main tank (initially E10, finally E02 gasoline)
- 3 gallons high octane tank (E70)
- Initially 15 gallons of E10 fuel is fed into the main tank
- Separation time will vary with separator conditions (here, about 1 hour or 40 miles)

**Driving Cycle Effects**
- Driving range reduction occurs for the aggressive cycle
- High octane fuel shortage when engine operated at MBT: spark retard required at some point
On-Board Separation System

Full Tank Scenario
- US06 cycle analyzed
- With MBT spark timing, E70 fuel runs out around 210 miles

Spark Retard Effects
- Driving range reduced from 345 to 320 to 282 miles, a 7% or 18% reduction in range, with up to 5 CAD, or up to 10 CAD retard.
- Up to 5 CAD retard gives effective use of high octane fuel.
Comparison: Two-Tank fill, and OBS

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<thead>
<tr>
<th></th>
<th>Two-tank</th>
<th>OBS</th>
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<tbody>
<tr>
<td>50% downsized engine, U.S. combined cycle, with up to 5CAD retard allowed</td>
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<tr>
<td>Fuel Economy</td>
<td>26% improvement compared to a single fuel engine</td>
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<tr>
<td>High Octane Fuel</td>
<td>Refueling frequency of 0.1</td>
<td>Supplies <strong>enough</strong> to finish driving cycle: easy replenishment</td>
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<td>Extra Cost</td>
<td>~ $43 Extra tank, fuel pumps, injectors, etc</td>
<td>~ $82 Heat exchangers, vacuum pump, membrane unit, etc</td>
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<tr>
<td>Added complexity</td>
<td>Low</td>
<td>High (membrane system and controls)</td>
</tr>
<tr>
<td>Consumer Impacts</td>
<td>High (refueling, second tank)</td>
<td>Low (no external refueling)</td>
</tr>
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System Comparison

- Numbers depend, some, on engine and fuels details
- For two-tank system, tank refueling frequency and ratio is important
- For OBS system, substantial system configuration flexibility (size, use pattern, cost, etc.)
- OBS requires additional components beyond what the two-tank system requires: cost estimates are preliminary
- For the two-tank system, refueling convenience and frequency, and high-octane fuel availability, are critical factors.
- **Fuel consumption benefits are significant**