Cold-Start Performance and Emissions Behavior of Alcohol Fuels in an SIDI Engine Using Transient Hardware-In-Loop Test Methods

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Motivation & Objectives

U.S. Renewable Fuel Standard requires an increase of ethanol and advanced biofuels to 36 billion gallons by 2022.

- Assess the potential of gasoline-alcohol fuel blends for use in a direct-injection (DI) spark-ignition (SI) engine.

- Utilize Engine Hardware-In-Loop capability to characterize emissions trends over a simulated test cycle.

iso-Butanol as possible advanced biofuel?

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Adapted from: Renewable Fuels Standard (Federal Register, 75(58))
## Comparison of Fuel Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Gasoline</th>
<th>Ethanol</th>
<th>iso-Butanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>C₄ - C₁₂</td>
<td>C₂H₅OH</td>
<td>C₄H₉OH</td>
</tr>
<tr>
<td>Composition (C, H, O)</td>
<td>Mass-%</td>
<td>86, 14, 0</td>
<td>52, 13, 35</td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>42.7</td>
<td>26.8</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>741</td>
<td>790</td>
</tr>
<tr>
<td>Octane number ((R+M)/2)¹</td>
<td>-</td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td>Stoichiometric air/fuel ratio</td>
<td>-</td>
<td>14.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Latent heat of vaporization²</td>
<td>kJ/kg</td>
<td>380 – 500</td>
<td>919</td>
</tr>
<tr>
<td>Boiling Point¹</td>
<td>°C</td>
<td>29 (IBP)</td>
<td>78</td>
</tr>
</tbody>
</table>

¹Measured for gasoline, typical reference values for alcohols
²Typical reference values

### Ethanol Blends

![Ethanol Blends](image1)

### iso-Butanol Blends

![iso-Butanol Blends](image2)
Engine Hardware-In-Loop Concept

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Experimental Methods: Cycle and Validation

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Gasoline Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECE-15</td>
<td>11.3 l/100km (Vehicle), 12.4 l/100km (Engine HIL)</td>
</tr>
<tr>
<td>EUDC</td>
<td>6.1 l/100km (Vehicle), 6.5 l/100km (Engine HIL)</td>
</tr>
<tr>
<td>NEDC</td>
<td>8.0 l/100km (Vehicle), 8.7 l/100km (Engine HIL)</td>
</tr>
</tbody>
</table>

**Fuel Consumption**

**Emissions**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Euro 4</th>
<th>Engine HIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>&lt; 0.1</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>CO</td>
<td>&lt; 1</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>HC</td>
<td>&lt; 0.068</td>
<td>0.03 ± 0.01</td>
</tr>
</tbody>
</table>
Experimental Methods for Fuels Testing

**Test Fuels**

<table>
<thead>
<tr>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>E50</td>
</tr>
<tr>
<td>E85</td>
</tr>
<tr>
<td>isoBut83</td>
</tr>
</tbody>
</table>

Constant oxygen content (18%-mass)

Comparable alcohol content

**Engine Modifications**

GM 2.2L Ecotec SIDI (European spec. engine, not ‘flex-fuel’)

ECU calibration change made for alcohol fuels
+18% fueling for E50/isoBut83
+30% fueling for E85
Conditions and Sampling Locations

Fuel variation:
Gasoline v. Ethanol Blends v. iso-Butanol Blend

**Hot-Start**
TWC at operational temperatures

- Pre-TWC Emissions
  - Emissions trends comparable to those of steady state data

- Post-TWC Emissions
  - Full conversion in TWC yields near-zero emissions

**Cold-Start**
TWC initially non-operational
Engine not at operating temperature

- Pre-TWC Emissions
  - Useful for diagnosing engine behavior

- Post-TWC Emissions
  - Levels are subject to regulation

Problematic for alcohol blends?
**Modified ‘Cold Start’ for High Alcohol Fuels**

**Initial Problem:** Engine would not start (reliably) with high alcohol blends

**Solution:** modified ‘cold-start’ procedure
- Motor engine at 1000 rpm until coolant temperature reaches 30°C
- Execute ‘cold-start’ (M30)
Cycle Emissions Results

NEDC, cold-start, post-TWC emissions
Hydrocarbon Mass Emissions with Time

NEDC, Cold-Start (M30), post-TWC hydrocarbon emissions
Hydrocarbon Levels Engine-Out

NEDC, cold-start (M30), pre-TWC hydrocarbon emissions
Combustion Instability with iso-Butanol83 During Initial Idle Period

NEDC, cold-start (M30), iso-Butanol83 fuel

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Cycles Misfiring</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>9</td>
</tr>
<tr>
<td>#2</td>
<td>74</td>
</tr>
<tr>
<td>#3</td>
<td>72</td>
</tr>
<tr>
<td>#4</td>
<td>40</td>
</tr>
</tbody>
</table>
Engine Behaviors Effecting ECU Responses

Engine not reaching targeted idle speed with isoBut83

Engine Underspeed at Idle

Increased Exhaust Oxygen Concentration

Higher O₂ levels in exhaust due to misfire
Engine Underspeed & System Reaction

Vehicle Command

ECU Command to Throttle
Lean Lambda Signal with *iso*-Butanol83 Misfire

Exhaust Oxygen Content

ECU Lambda Signal

O₂ in exhaust due to misfire
Increased Fuel Flow with \textit{iso}-Butanol83

Excessive Fuel Flow

Measured Fuel Flow

Injection at Time = 6 s.
Conclusions & Future Opportunities

- Highlights cold-start as a significant limitation to the “drop-in” potential of high level iso-butanol blends as a gasoline replacement fuel.

- Persistent misfire during initial cold-start idle period responsible for high HC emissions, and failure to meet emissions targets, using blend of 83% iso-butanol with gasoline.

- Comparable behavior was not attained with near matched blend of ethanol and gasoline (E85).

- Opportunities lie in (1) development of cold-start control strategies for high alcohol fuels like iso-butanol and (2) developing a detailed understanding physical behavior of fuels under initial engine start conditions.
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