Technology And Cost Of
Sulfur Reduction In
Transportation Fuels

Central America Regional Workshop
Fuel Quality
Michael P. Walsh

Overview

• Why Low Sulfur Fuels
• How To Reduce Sulfur in Both Gasoline and Diesel
• International Experience Regarding The Benefits and Costs of Reducing Sulfur

Tons of Directly Emitted PM From Diesel Fuels Sulfur

Increase in In-Use Vehicle Emissions in Bangkok Due To Sulfur in Fuel (Gasoline)
**Increase in In-Use Vehicle Emissions in Bangkok Due To Sulfur in Fuel (Diesel)**

- **HC**: 54% increase at 350 ppm, 33% increase at 500 ppm
- **NOx**: 0% increase at 350 ppm, 10% increase at 500 ppm
- **PM**: 5% increase at 350 ppm, 16% increase at 500 ppm

Impact on Vehicles Meeting EURO 3 Standards

**Other Benefits from Sulfur Control**

- **Sulfur reduction reduces SO2 emissions.**
  - Less sulfate formation in the atmosphere (about 1/3 of SO2 reacts to sulfate)
  - Reduced acid rain.
- **Sulfur reduction reduces engine wear.**
  - Reduction from 2500 ppm to 500 ppm reduces engine wear 10 - 20%; about 33% if starting out at 5000 ppm.
  - Greater engine wear with infrequent oil change.
- **Allows More Advanced Vehicle Technologies**
- **Retrofit Opportunities**

**What a refinery does:**

- Converts crude oil to usable products
- Adjusts yields to match product demand
- Adjusts qualities to meet product specifications.

**Typical Refinery Products**

- Liquefied Petroleum Gas (LPG)
- Naphtha (for petrochemical feed)
- Motor Gasoline
- Distillates (Jet, Diesel, Heating Oil)
- Lubricants, Waxes
- Fuel Oil
- Asphalt
### Crude Oil Characteristics – Sulfur

<table>
<thead>
<tr>
<th>Product</th>
<th>Sweet Crude (PPM Sulfur)</th>
<th>Sour Crude (PPM Sulfur)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Jet/Kerosene</td>
<td>500</td>
<td>4000</td>
</tr>
<tr>
<td>Distillate</td>
<td>2000</td>
<td>10000</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>6500</td>
<td>30000</td>
</tr>
</tbody>
</table>

### Types of Refinery Processes

- **Physical Separation Processes**
  - Distillation/Fractionation
  - Extraction

- **Chemical Processes**
  - Cracking/Conversion
  - Combination/Reformulation
  - Hydrotreating

### Refinery Configuration Overview

- **Topping** – Simple crude separation, no ability to change yield and quality
- **Hydroskimming** – Simple crude separation, no ability to adjust yield. Can increase octane, lower sulfur
- **Conversion** – Yield adjustment capability and quality improvement
- **Deep Conversion** – Large yield/quality flexibility, fuel oil minimization

### Topping Refinery

- Crude 1000 MBPD
- 3R Naphtha 400 F
- Kerosene 500 F
- Diesel 700 F
- Atm. Residue 700+ F
- LPG 1
- Fuel Oil 3
Hydroskimming Refinery

Reformer

- SR Naphtha is hydrotreated and split.
- Heavy part (Heavy Naphtha) is catalytically processed and reformed to a highly aromatic stream called Reformate.
  - Advantages:  
    - High octane product
    - Hydrogen also a product
  - Disadvantages: Aromatics are toxic and are limited in clean fuel specs.

C5C6 Isomerization

- Straight chain paraffins are catalytically converted to their chain counterparts.
- Advantages:  
  - 10 to 12 numbers octane gain
  - Elimination of toxic benzene
- Disadvantage: Product has higher RVP

Diesel Hydrodesulfurization (HDS)

- Standard Diesel HDS:  
  - Sulfur is catalytically removed in the presence of hydrogen
- Deep HDS  
  - Higher activity catalyst and catalyst volume
  - More hydrogen consumed
  - High severity, high pressure operation
  - Loss of diesel yield
Conversion Refinery
Catalytic Cracking (FCC)

Fluid Catalytic Cracking (FCC)
- Vacuum and coker gasoil feeds
- Makes gasoline out of vacuum gasoil (a stream heavier than diesel).
- Using intense heat (about 1,000 deg F), low pressure and a powdered catalyst, the cat cracker converts heavy fractions into smaller gasoline molecules
- Product streams typically have high sulfur content

Alkylation
- Combines FCC gas (propylenes/butylenes) with isobutane to produce a high octane stream called alkylate.
- Catalyst is sulfuric or hydrofluoric acid
- Alkylate is an excellent diluent for other gasoline blending components.

Diesel HDS and Aromatic Saturation
- Necessary for FCC LCO treatment
- 1st stage - requires Diesel HDS
- 2nd stage – aromatic saturation with noble catalysts
  - Process consumes hydrogen
  - Gains of 17 to 23 cetane numbers are possible
**Hydrocracking**

- Similar and preferably lighter feeds than cat cracking
- More flexible. Can optionally maximize gasoline, jet or diesel
- Uses a different catalyst, much greater pressure than FCC and a lot of hydrogen
- Products have minimal sulfur

---

**Visbreaking**

- Also vacuum residue feed
- Mild form of thermal cracking. Reduces viscosity of residue
- Produces small quantity of diesel.

---

**Coking**

- Vacuum residue feed
- Thermal cracking process. No catalyst involved.
- Use heat and moderate pressure to turn heavy residues to lighter products and coke (a hard coal-like substance used as an industrial fuel).
**Blending**

- Blending is the physical mixture of a number of refinery streams to a finished product.
- Options include:
  - Batch blending via manifolds into a tank
  - In-line blending via injection of proportionate components into a main stream
- Additives/Improvers such as octane enhancers, detergents etc. are added before or after blending

**Gasoline Blending Component Qualities**

<table>
<thead>
<tr>
<th></th>
<th>Light Naphtha</th>
<th>Isomerate</th>
<th>Reformate</th>
<th>FCC Gasoline</th>
<th>C4 Alkylate</th>
<th>MTBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur, PPM</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>1200</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Research Octane</td>
<td>72</td>
<td>92</td>
<td>93</td>
<td>96</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>Benzene, vol%</td>
<td>1.2</td>
<td>5.5</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Aromatics, vol%</td>
<td>2</td>
<td>65</td>
<td>26</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>RVP, psi</td>
<td>12</td>
<td>14</td>
<td>5</td>
<td>7.4</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

**Clean Gasoline Quality Changes**

**Moderate sulfur reduction**

- Run crudes with lower sulfur content
  - Pricier. Not always possible
- Distillation tailoring/undercutting
  - Loss of gasoline volume
- Dilute sulfur with alcohol blending
  - Pricier. Availability issues

**Severe sulfur reduction**

- Hydrotreat naphthas and FCC gasoline
  - Higher capital expenditure. Some octane loss.
- Desulfurize FCC feed
  - Higher capital cost.
### Gasoline Sulfur Reduction Example

#### Base, Low Sulfur, Fractionate

<table>
<thead>
<tr>
<th>Blend Stream</th>
<th>Vol Base</th>
<th>PPM S</th>
<th>Octane</th>
<th>Vol LS Crack</th>
<th>PPM S</th>
<th>Octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lt Naphtha</td>
<td>5</td>
<td>120</td>
<td>66</td>
<td>2</td>
<td>120</td>
<td>66</td>
</tr>
<tr>
<td>Reformate</td>
<td>21</td>
<td>0</td>
<td>93</td>
<td>21</td>
<td>0</td>
<td>94</td>
</tr>
<tr>
<td>FCC Gasoline</td>
<td>48</td>
<td>600</td>
<td>88.5</td>
<td>2</td>
<td>600</td>
<td>86.5</td>
</tr>
<tr>
<td>Trt FCC</td>
<td>4</td>
<td>14</td>
<td>50</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>10</td>
<td>93</td>
<td>10</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>215</td>
<td>87.5</td>
<td>48</td>
<td>46</td>
<td>87.5</td>
</tr>
</tbody>
</table>

### Distillate Blending Component Qualities

<table>
<thead>
<tr>
<th>Quality</th>
<th>SR Diesel</th>
<th>HKR Diesel</th>
<th>Thermal Diesel</th>
<th>FCC LCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur, wppm:</td>
<td>1,000 - 5,000</td>
<td>30 – 50</td>
<td>10,000 - 20,000</td>
<td>1,000 - 20,000</td>
</tr>
<tr>
<td>Gravity, API:</td>
<td>34</td>
<td>44</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>Aromatics, vol%</td>
<td>20</td>
<td>10</td>
<td>45</td>
<td>78</td>
</tr>
<tr>
<td>PNA, wt%</td>
<td>10</td>
<td>2</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Distillation, 95% F</td>
<td>690</td>
<td>690</td>
<td>660</td>
<td>670</td>
</tr>
</tbody>
</table>

### Diesel Sulfur Reduction Example

#### Base, Low Sulfur, Fractionate

<table>
<thead>
<tr>
<th>Blend Stream</th>
<th>Vol Base</th>
<th>PPM S</th>
<th>Vol LS Crack</th>
<th>PPM S</th>
<th>Vol LS Crack</th>
<th>PPM S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>15</td>
<td>2000</td>
<td>15</td>
<td>500</td>
<td>15</td>
<td>2000</td>
</tr>
<tr>
<td>Distillate</td>
<td>48</td>
<td>5500</td>
<td>15</td>
<td>2000</td>
<td>15</td>
<td>5300</td>
</tr>
<tr>
<td>FCC LCO</td>
<td>2</td>
<td>17500</td>
<td>3</td>
<td>6000</td>
<td>3</td>
<td>13000</td>
</tr>
<tr>
<td>Trt Dist.</td>
<td>17</td>
<td>870</td>
<td>17</td>
<td>500</td>
<td>17</td>
<td>500</td>
</tr>
<tr>
<td>Trt Dist. (Severe)</td>
<td>35</td>
<td>2360</td>
<td>32</td>
<td>500</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>5000</td>
<td>33</td>
<td>1680</td>
<td>33</td>
<td>3860</td>
</tr>
</tbody>
</table>

### Diesel Sulfur Reduction Example

#### HDS, Full HDS, Severe HDS

<table>
<thead>
<tr>
<th>Blend Stream</th>
<th>Vol Base</th>
<th>PPM S</th>
<th>Vol LS Crack</th>
<th>PPM S</th>
<th>Vol LS Crack</th>
<th>PPM S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>15</td>
<td>2000</td>
<td>15</td>
<td>500</td>
<td>15</td>
<td>2000</td>
</tr>
<tr>
<td>Distillate</td>
<td>48</td>
<td>5500</td>
<td>15</td>
<td>2000</td>
<td>15</td>
<td>5300</td>
</tr>
<tr>
<td>FCC LCO</td>
<td>2</td>
<td>17500</td>
<td>3</td>
<td>6000</td>
<td>3</td>
<td>13000</td>
</tr>
<tr>
<td>Trt Dist.</td>
<td>17</td>
<td>870</td>
<td>17</td>
<td>500</td>
<td>17</td>
<td>500</td>
</tr>
<tr>
<td>Trt Dist. (Severe)</td>
<td>35</td>
<td>2360</td>
<td>32</td>
<td>500</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>5000</td>
<td>33</td>
<td>1680</td>
<td>33</td>
<td>3860</td>
</tr>
</tbody>
</table>
The Costs and Benefits of Shifting To Lower Sulfur Fuels
International Experience

- US
- Canada
- European Union
- Asia Countries
- China

Estimates of benefits
(Source: US EPA RIA, 2000)

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Number of Annual Cases for All of US 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>New cases of bronchitis</td>
<td>5,600</td>
</tr>
<tr>
<td>New cases of chronic bronchitis</td>
<td>5,500</td>
</tr>
<tr>
<td>Acute asthma attacks</td>
<td>361,400</td>
</tr>
<tr>
<td>Acute respiratory symptoms</td>
<td>386,000</td>
</tr>
<tr>
<td>Restricted activity days</td>
<td>9.5 million</td>
</tr>
<tr>
<td>Hospital Admissions</td>
<td>8,300</td>
</tr>
<tr>
<td>Emergency Room Visits</td>
<td>5,100</td>
</tr>
<tr>
<td>Mortality</td>
<td>17,600</td>
</tr>
</tbody>
</table>

Assessing Health Benefits of US Diesel Fuel and Technology Rules

- New US EPA rules to reduce diesel fuel sulfur and engine emissions
  - Fuel sulfur from 500 ppm to 15 ppm in 2006
  - Reduced PM and NOx emissions in 2007, 2010
- Accepted by US Office of Management and Budget

Costs and Benefits of Low Sulfur Diesel Fuel (<15 PPM) and Very Stringent Heavy Duty Engine Standards in the US

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Billions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Costs</td>
<td>$0</td>
</tr>
<tr>
<td>Annual Scenario</td>
<td>$70</td>
</tr>
<tr>
<td>Net Annual Benefits</td>
<td>$66</td>
</tr>
</tbody>
</table>
Results of Three Major US Rules

**Benefits Costs Net Benefits**

<table>
<thead>
<tr>
<th>Billions</th>
<th>Benefits</th>
<th>Costs</th>
<th>Net Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>$10</td>
<td>$10</td>
<td>$0</td>
<td>$10</td>
</tr>
<tr>
<td>$20</td>
<td>$20</td>
<td>$0</td>
<td>$20</td>
</tr>
<tr>
<td>$30</td>
<td>$30</td>
<td>$0</td>
<td>$30</td>
</tr>
<tr>
<td>$40</td>
<td>$40</td>
<td>$0</td>
<td>$40</td>
</tr>
<tr>
<td>$50</td>
<td>$50</td>
<td>$0</td>
<td>$50</td>
</tr>
<tr>
<td>$60</td>
<td>$60</td>
<td>$0</td>
<td>$60</td>
</tr>
<tr>
<td>$70</td>
<td>$70</td>
<td>$0</td>
<td>$70</td>
</tr>
<tr>
<td>$80</td>
<td>$80</td>
<td>$0</td>
<td>$80</td>
</tr>
<tr>
<td>$90</td>
<td>$90</td>
<td>$0</td>
<td>$90</td>
</tr>
</tbody>
</table>

**Tier 2 Standards & Low Sulfur Gasoline**

- HD Diesel Standards & ULSD
- Off Road Diesel Standards & ULSD

**Health Effects Consensus Findings**

(Independent Expert Panel)

Reducing sulphur to 30 ppm improves the health of Canadians

**Number of Cases**

- Mortality: 21,000
- Hospital Admissions: 6,800
- Emergency Room Visits: 9,000
- Restricted activity days: 1.6 million
- Acute respiratory symptoms: 3.3 million
- New cases of croup, pneumonia: 8,700
- New cases of bronchitis in children: 11 million
- New cases of chronic bronchitis: 2,300

**EU Estimate of Costs to Reduce Sulfur From 50 ppm to 10 ppm**

- Gasoline: Low Estimate $0.29, High Estimate $0.41
- Diesel: Low Estimate $0.25, High Estimate $0.50

**Health Effects of Pollution**

Mixture May Be Much Greater Than Particles Alone

**Canadian Study of Health Impacts of Low Sulfur Gasoline**

Costs and benefits calculated for the years 2001 - 2020.

Costs calculated country wide; benefits for seven cities including Toronto, Montreal, Vancouver, Halifax, Winnipeg, St. John, and Edmonton.

**Emission Reductions**

<table>
<thead>
<tr>
<th>0.00 ppm sulphur level</th>
<th>Costs in billions of $CDN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>Benefits</td>
</tr>
<tr>
<td>$0.11</td>
<td>$0.29</td>
</tr>
<tr>
<td>$0.20</td>
<td>$0.40</td>
</tr>
<tr>
<td>$0.25</td>
<td>$0.46</td>
</tr>
<tr>
<td>$0.30</td>
<td>$0.50</td>
</tr>
<tr>
<td>$0.35</td>
<td>$0.55</td>
</tr>
<tr>
<td>$0.40</td>
<td>$0.60</td>
</tr>
<tr>
<td>$0.45</td>
<td>$0.65</td>
</tr>
<tr>
<td>$0.50</td>
<td>$0.70</td>
</tr>
</tbody>
</table>

1 Costs and benefits calculated for the years 2001 - 2020.
Costs for China

- Costs ranged from 2.8 to 3.2 c/g inclusive in 2005, 4.04 c/g in 2006, 4.7 c/g in 2010 except for EURO5 5.2 c/g.
- Diesel costs were roughly twice gasoline costs.
- Costs are well within acceptable parameters by US and European standards.
- Benefits may include emissions, fleet maintenance, fuel harmonization, ability to export

Conclusions

- Low Sulfur Fuel Reduces Emissions
- Refinery Processes For Reducing Sulfur From Both Gasoline and Diesel Are Well Known and Improving
- Costs Are Quite Reasonable
- Benefits Far Outweigh The Costs