

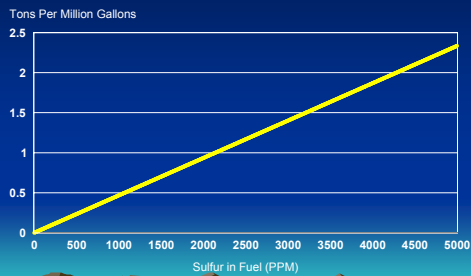
Technology And Cost Of Sulfur Reduction In Transportation Fuels

Central America Regional Workshop
Fuel Quality
Michael P. Walsh

Overview

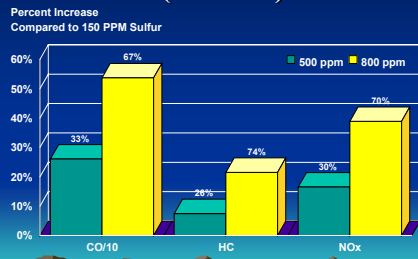
- Why Low Sulfur Fuels
- How To Reduce Sulfur in Both Gasoline and Diesel
- International Experience Regarding The Benefits and Costs of Reducing Sulfur

Tons of Directly Emitted PM From Diesel Fuels Sulfur



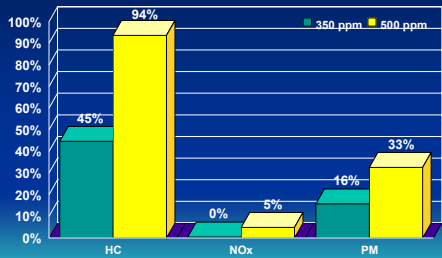
Derived From US EPA Data

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



Impact on Vehicles Meeting EURO 3 Standards

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



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

Sweet vs Sour Crude

| Product | Sweet Crude (PPM Sulfur) | Sour Crude (PPM Sulfur) |
|--------------|-----------------------------|----------------------------|
| Naphtha | 100 | 400 |
| Jet/Kerosene | 500 | 4000 |
| Distillate | 2000 | 10000 |
| Fuel Oil | 6500 | 30000 |

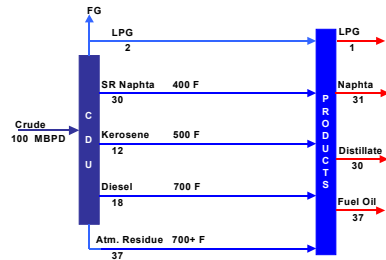
Types of Refinery Processes

- Physical Separation Processes
 - Distillation/Fractionation
 - Extraction
- Chemical Processes
 - Cracking/Conversion
 - Combination/Reformulation
 - Hydrotreating

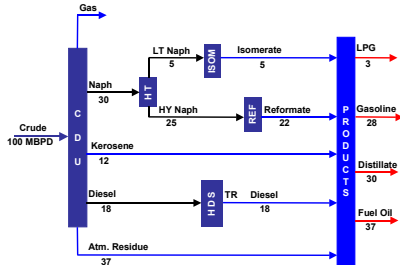
Refinery Configuration Overview

- **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



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.

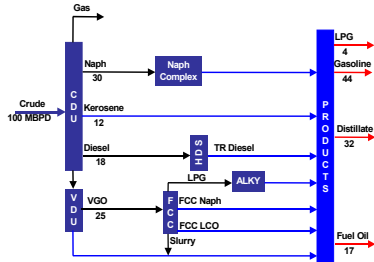
C5C6 Isomerization

- 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

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

| | Light Naphtha | Isomerate | Reformate | FCC Gasoline | C4 Alkylate | MTBE |
|-----------------|---------------|-----------|-----------|--------------|-------------|------|
| Sulfur, PPM | 200 | 0 | 0 | 1200 | 5 | 2 |
| Research Octane | 72 | 82 | 92 - 98 | 93 | 96 | 118 |
| Benzene, vol% | 1.2 | 0.2 | 5.5 | .5 | 0 | 0 |
| Aromatics, vol% | 2 | 0.2 | 65 | 26 | 0 | 0 |
| RVP, psi | 12 | 14 | 5 | 7.4 | 7 | 8 |

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**
 - Pricy. Availability issues

Clean Gasoline Quality Changes

Severe sulfur reduction

- **Hydrotreat naphthas and FCC gasoline**
 - Higher capital expenditure. Some octane loss.
- **Desulfurize FCC feed**
 - Higher capital cost.

Gasoline Sulfur Reduction Example

| Blend Stream | Vol Base | PPM S | Octane | Vol Low S | PPM S | Octane |
|----------------------------|-----------|------------|-------------|-----------|-----------|-------------|
| Lt Naphtha | 6 | 120 | 66 | 2 | 120 | 66 |
| Reformate | 21 | 0 | 93 | 21 | 0 | 94 |
| FCC Gasoline | 15 | 600 | 86.5 | 3 | 600 | 86.5 |
| Trt FCC Gasoline Isomerate | | | | 14 | 50 | 81 |
| | | | | 4 | 0 | 81 |
| Other | 6 | 10 | 93 | 6 | 10 | 93 |
| Total | 48 | 215 | 87.5 | 48 | 46 | 87.5 |

Distillate Blending Component Qualities

| Quality | SR Diesel | HKR Diesel | Thermal Diesel | FCC LCO |
|----------------------|---------------|------------|----------------|---------------|
| Sulfur, wppm: | 1,000 - 5,000 | 30 - 50 | 10,000,-20,000 | 1,000 -20,000 |
| Gravity, API: | 34 | 44 | 29 | 16 |
| Aromatics, vol% | 20 | 10 | 45 | 78 |
| PNAs, wt% | 10 | 2 | 25 | 53 |
| Distillation, 95% F: | 690 | 690 | 660 | 670 |

Diesel Sulfur Reduction Example Base, Low Sulfur, Fractionate

| Blend Stream | Vol Base | PPM S | Vol LS Crude | PPM S | Vol Frac. | PPM S |
|--------------------|-----------|-------------|--------------|-------------|-----------|-------------|
| Kerosene | 15 | 2000 | 15 | 500 | 15 | 2000 |
| Distillate | 15 | 5500 | 15 | 2000 | 13 | 5300 |
| FCC LCO | 3 | 17500 | 3 | 6000 | 1 | 13000 |
| Trt Dist. | | | | | | |
| Trt Dist. (Severe) | | | | | | |
| Total | 33 | 5000 | 33 | 1680 | 29 | 3860 |

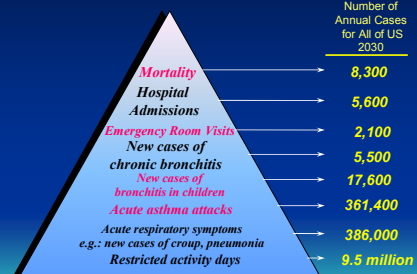
Diesel Sulfur Reduction Example HDS, Full HDS, Severe HDS

| Blend Stream | Vol | PPM S | Vol | PPM S | Vol | PPM S |
|--------------------|-----------|-------------|-----------|------------|-----------|-----------|
| Kerosene | 15 | 2000 | 0 | 2000 | 0 | 2000 |
| Distillate | 7 | 5500 | 0 | 5500 | 0 | 5500 |
| FCC LCO | 0 | 17500 | 0 | 17500 | 0 | 17500 |
| Trt Dist. | 11 | 870 | 32 | 500 | 0 | 500 |
| Trt Dist. (Severe) | | | | | 31 | 20 |
| Total | 33 | 2360 | 32 | 500 | 31 | 20 |

The Costs and Benefits of Shifting To Lower Sulfur Fuels International Experience

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

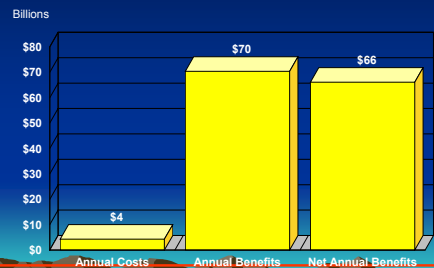
Estimates of benefits (Source: US EPA RIA, 2000)



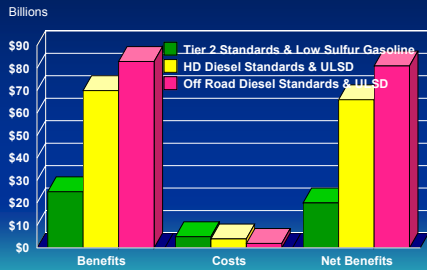
Assessing Health Benefits of US Diesel Fuel and Technology Rules

- 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
- EPA conducted extensive Regulatory Impact Analyses (2000)
- 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



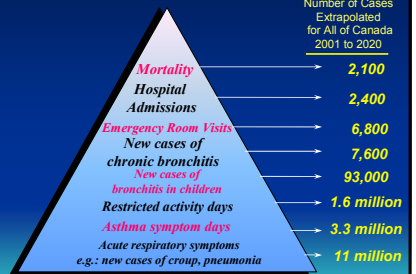
Results of Three Major US Rules



Health Effects Consensus Findings (Independent Expert Panel)

Reducing sulphur to 30 ppm improves the health of Canadians

Health Effects of Pollution Mixture May Be Much Greater than Particles Alone

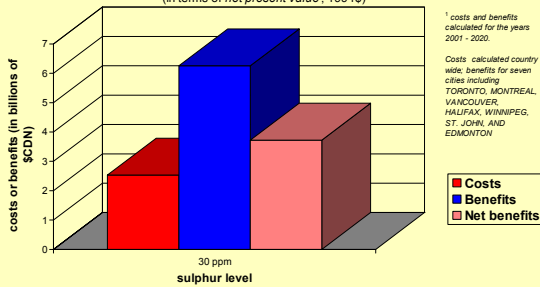


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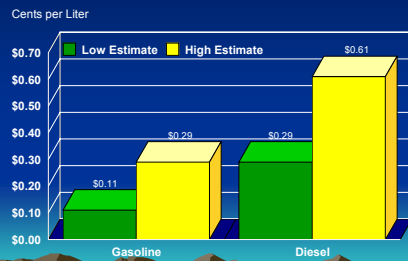
Canadian Study of Health Impacts of Low Sulfur Gasoline

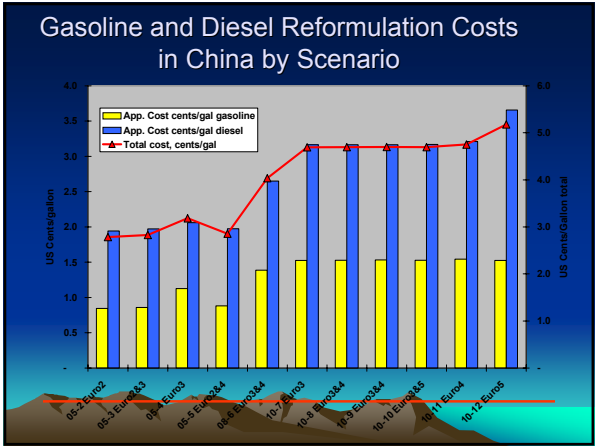
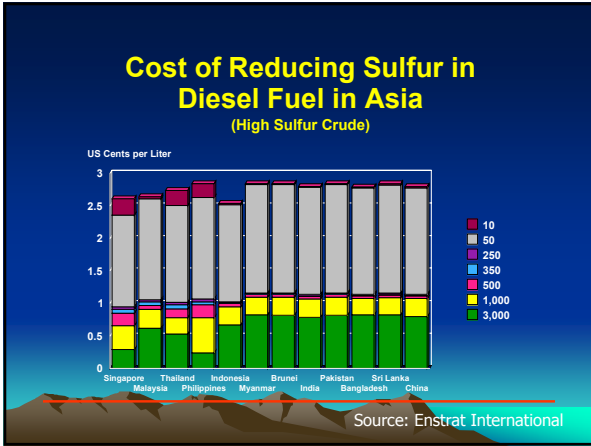
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Costs and benefits of reduced-sulphur gasoline¹ (in terms of net present value; 1994\$)



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





Costs for China

- Costs ranged from 2.8 to 3.2 c/g inclusive in 2005, 4.04 c/g in 2008, 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