Refining and automobile—technical issues and costs to consider when designing fuel quality strategies

Module 2 looks at key refining and automotive technology options and addresses technical restrictions and relevant investment issues linked to conventional fuel quality changes.

Explanatory section—the refining industry

One of the main building blocks of the fuel quality pillar is an analysis of technology options and Best Available Technologies/Techniques (BAT). When developing a fuel quality strategy, regulators are often confronted with numerous costs regarding the implementation of cleaner fuel quality specifications. These costs, which tend to be presented by the oil industry, are usually very detailed and refer to the complexity of refining technology and the uniqueness of refinery configurations across the globe. Most regulators do not have the technical expertise to truly assess these costs, nor should they necessarily, but what is important is to have at least some broad understanding of different refining technology and BAT options. This module attempts to assist in the development of this broad knowledge base.

The petroleum industry was developed with the successful drilling of the first commercial oil well in 1859, and the opening of the first refinery in the U.S. two years later. The original demand for oil was to produce kerosene as a cheaper and better source of light than whale oil. It was only in the late 1800’s with the development of the internal combustion engine, that gasoline and diesel fuels were produced. Then the evolution of the airplane created a need first for high-octane aviation gasoline and then for jet fuel, a sophisticated form of the original product, kerosene. Due to the development of these different transport modes, and the demand for refined oil products, present-day refineries, as illustrated in figure 2.1, now produce a variety of products including many required as feedstock for the petrochemical industry.

When looking at these different products, it is important to keep in mind that although every refinery is built on the same concept of converting crude into useable and valuable products, they are all different! Each refinery configuration is extremely complex and unique.

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Products produced by refineries

as it depends on many variables. A few of those variables are:

- Requested product demand either from local and/or export market(s),
- Product quality requirements,
- Availability of raw materials,
- Date of construction,
- Technology availability,
- Financing availability.

Today, most refiners are built or altered to optimise the production of either gasoline and/or diesel.

**Crude oil impact on automotive fuel quality**

The key role of an oil refinery is to turn crude oil, which has limited use as raw material, into a refined product suitable for end use consumption. Raw crude oil straight from the well is a complex mixture of chemicals classified as hydrocarbons, consisting primarily of carbon and hydrogen. Crude oil contains thousands of different hydrocarbon molecules, which collectively determine its physical and chemical characteristics and the type and degree of refining required to produce a desired menu of refined products. Crude oil also contains non-hydrocarbon chemicals, such as sulfur, which will impact refining requirements as well as product quality. Within the refinery, high sulfur levels can lead to corrosive mixtures and undesirable air emissions of sulfur compounds. Additionally, as we have seen in Module 1, sulfur in automotive fuels also leads to undesirable emissions of sulfur compounds and can interfere with vehicle emission control systems.

The quality, or chemical makeup, of crude oil will vary considerably between production fields and therefore will require varying configurations of refining and/or will limit refined product yield. The primary quality parameter used to characterize crude oil is its gravity (density),
which provides an indication of how light or heavy the crude is. A lighter crude contains a larger portion of smaller molecules characteristic of gasoline and other transportation fuels. A heavier crude contains a greater portion of larger molecules found in heavy industrial fuels, asphalt, etc., for which there are more limited markets.

Figure 2.2 shows the quality range of light (API of 35) versus heavy crude (API of 25) in terms of the natural yield of light gas, gasoline, middle distillate and heavy oils. Also shown for comparison is a breakdown of the demand for the same product categories. Light crude oil contains roughly 68 percent of gasoline and distillate (diesel) material and 30 percent heavier oils. In comparison the heavy crude oil contains only 29 percent of the lighter gasoline/distillate and 70 percent of heavy oil.

In contrast, gasoline/distillate demand in Asia represents about 78 percent of all refined product and heavy fuel makes up only 14 percent. The yield of heavy product from either the light or heavy crude is greater than demand and therefore some heavy material must be transformed to lighter material through the refining process (as discussed in following sections). Furthermore, the yield of heavier oil from the heavier crude is more than twice that of the light crude indicating a greater refinery conversion requirement.

Crude oils are also classified by sulfur content that, like gravity, varies significantly across crude types. Typically crude is referred to as sweet (low sulfur) when its sulfur level is less than 5,000 ppm and sour (high sulfur) above this level. The majority of sour crude has sulfur levels in the 10,000 ppm to 20,000 ppm range, but can contain sulfur in excess of 40,000 ppm. Crude with sulfur in the 5,000 to 1,000-ppm range are sometimes referred to as intermediate sulfur crude.

Asian refineries traditionally have had access to relatively low sulfur local crudes as seen in table 2.1. This remains true of much Asian crude production. However, with demand through the 1990’s rising sharply at the same time as local supply failed to increase, the region has increasingly had to buy higher sulfur crudes from elsewhere.

There has been a sharp increase in imports of light, relatively low sulfur West African crudes but imports from the Middle East have also risen. As mentioned under Module 1, 90% of imported crude to the Asian region is from the Middle East. Continued growth is expected in crude imports from these regions as well.

<table>
<thead>
<tr>
<th>Crude type</th>
<th>Sulfur level (ppm)</th>
<th>API gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabian Light</td>
<td>19,000</td>
<td>34.0</td>
</tr>
<tr>
<td>Arabian Heavy</td>
<td>28,500</td>
<td>28.5</td>
</tr>
<tr>
<td>China – Daqing</td>
<td>1,000</td>
<td>32.3</td>
</tr>
<tr>
<td>North Sea – Brent</td>
<td>4,000</td>
<td>37.0</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>1,500</td>
<td>35.8</td>
</tr>
</tbody>
</table>

as from Russia, which will increasingly become a more important source. Due to the expected growth in higher sulfur crude imports, this will inevitably lead to requirements for more complex processing, especially when combined with the need to make cleaner fuels.

**Automotive fuel blending**

Before discussing refining processes and technologies it is important to understand that the blending of automotive fuels is a very complex process and depends on legislative restrictions, raw material availability, product and process availability, and cost-effectiveness. Some flexibility is available to refiners who can export to areas with less restrictive specifications, or who are not regulated on all of their products.

As seen in previous Module, globally fuel quality trends are apparent. In all countries around the world, although at different stages, the trend is to eliminate lead, reduce benzene and aromatics, reduce vapour pressure and density, distillate curve control, increase octane and cetane numbers, and reduce sulfur content.

As summarized in Table 2.2, for each restriction on a fuel quality property refiners face different key issues all with varied solutions.

Table 2.2 shows that the more restrictions added to the refining product(s) the more alternatives a refiner needs to be able to meet such specifications. Less complex refiners (toppers, skimmers) have fewer alternatives available than the more complex (conversion) refineries. For some refiners new specifications might even be too restrictive for them to remain viable, and as a result the refining industry might see some degree of rationalization.

<table>
<thead>
<tr>
<th>Fuel quality change</th>
<th>Key issues</th>
<th>Key solutions/limitations</th>
</tr>
</thead>
</table>
| Lead phase out in gasoline | Selecting alternative octane sources | • Increased use of butane. Cheapest source of high octane replacement however it's use is limited by its high RVP.  
• Increased use of oxygenates. Good blending properties with extremely high motor and research octane number. Availability depends on refinery processes and import possibilities.  
• Increased use of catalytic reforming. Where capacity available, may be able to increase octane of product at low cost. New capacity is high cost. Reforming option again is limited by availability and possible benzene and aromatic restrictions.  
• Increased use of alkylate with great blending properties however its use is limited by availability. Alkylation relies on catalytic cracking or petrochemical operations for feed. New alkylation capacity is expensive.  
• Increased gasoline production from FCC unit that again might be a limited possibility for refineries faced with olefin, sulfur, and aromatics restrictions.  
• Increased use of isomerisation. Capacity costs are moderate. Total amount of octane improvement available is limited and isomerisation use may be limited by RVP. |
<table>
<thead>
<tr>
<th>Fuel quality change</th>
<th>Key issues</th>
<th>Key solutions/limitations</th>
</tr>
</thead>
</table>
| Reduced RVP in gasoline             | Reduced benzene content in gasoline            | - Limit use of butane by minimizing direct butane blending and Optimizing cut point of gasoline fractionation. May require low cost refinery fractionation investment. Will reduce octane.  
- Increased use of ethers provides the volume and reduced vapour pressure.  
- Make up octane loss with reforming or isomerisation as above. |
| Reduced benzene content in gasoline | Removal of benzene and aromatics contents lead to reduced volume and octane components | - Implement benzene extraction facilities. Extremely high cost and reduces gasoline volume.  
- Increased use of ethers, alcohols and/or alkylates provide the dilution because of added volume and high-octane substitutes. Limited availability as above.  
- Modify fraction on crude units to minimize benzene formation in gasoline streams. May require low cost fractionation investment and may result in some octane loss.  
- Modify fractionation and utilize isomerisation to minimize benzene formation in gasoline, reduce benzene in some streams and provide makeup octane.  
- Implement Benzene Saturation facilities. Moderate to high investment cost and some loss of octane. |
| Increased octane number             | Increased use of high-octane components         | - Similar solutions as for lead besides not only octane needs to be replaced but also volume. |
| Progressive reduction in gasoline sulfur content | Remove sulfur from raw material or blending stream. Processing options might reduce octane. | - Increased use of crude with low sulfur content.  
- Optimise cut point of gasoline fractionation (heavier portion of gasoline shifted to distillate). Reduced production of desired product.  
- Hydrotreat gasoline related streams. High cost and results in octane loss that may be replaced with options discussed above.  
- Increased use of ethers, alcohols and/or alkylates provide the dilution because of added volume and high-octane substitutes. Limited availability as above.  
- Desulfurize catalytic cracking feed. Extremely expensive, but will provide some yield and diesel sulfur reduction benefits. |
| Progressive reduction in diesel sulfur content | Remove sulfur from raw material or blending stream | - Increased use of crude with low sulfur content.  
- Optimise cut point of diesel fractionation (heavier portion of diesel shifted to other distillate uses or heavy fuel oil). Lead to reduction in diesel product production.  
- Hydrotreat the stream used for diesel. For first reduction steps use conventional processing (removal of about 90 percent of sulfur from feed). Treating larger portion of diesel streams will progressively reduce sulfur. For lower sulfur steps, utilize more severe procession (higher investment and operation cost). For very low sulfur must treat all diesel blend streams. |
**Fuel quality change**  |  **Key issues**  |  **Key solutions/limitations**  
---|---|---
Increased cetane number | Increased cetane is related to reduced aromatics content | • Desulfurize catalytic cracking feed. Extremely expensive, but will provide some yield and gasoline sulfur reduction benefits.  
• Install hydrocrackers. Extremely expensive but provides refinery flexibility to increase light product production, particularly low sulfur distillates.  
• Hydrotreaters/hydrocracking options require varying degrees of hydrogen production.  
• GTL diesel. Extremely expensive, but ultra low sulfur diesel with excellent properties.
Reduced aromatic content in diesel | Reduced aromatics is related to increased cetane | • Introduction of cetane additives/improvers that might be a cheaper alternative than reducing aromatics. Engine testing facilities required.  
• Instalment of advanced desulfurization or hydrocracking systems. May be extremely expensive and have very high hydrogen requirements.  
• Changing distillation operation however might lead to reduced production of desired product.  
• Instalment of advanced desulfurization or hydrocracking systems as above.


**Different refining configurations related to automotive fuel qualities**

A refinery’s configuration refers to the type, size, number of process technologies and facilities employed, and the flow sequence. Refinery configurations depend on what crude oil quality, product mix and quality, and environmental, safety, economic or other constraints were specified with its design. No two refineries are exactly alike, but refineries can be characterized into generic groups defined by the availability of the technologies.

A refinery’s complexity is typically referred to within four configurations. These configurations are listed in table 2.3 together with their available process technologies and their yields.

The most basic refining configuration, referred to as the topping refinery, consists of only crude distillation and basic support operations. The topping refinery separates the crude oil into light gas and refinery fuel, naphtha, distillates (kerosene, jet fuel, diesel and heating oils), and residual or heavy fuel oil. The naphthas are gasoline boiling range materials, a portion of which may be suitable as very low octane gasoline in some cases. The volume and quality of all the products is entirely dependent on the crude oil feed. The topping refinery flow and typical yields (based on an average quality crude) are given in figure 2.3.

The next level of refining complexity is the hydroskimming configuration. A typical simple hydroskimming configuration includes crude distillation, hydrotreating and blending while a more advanced hydroskimming refinery, as illustrated in figure 2.4, also includes catalytic reforming. The reforming capacity allows naphtha to be upgraded to gasoline octane quality and provides hydrogen needed for any hydrotreating employed. The hydrotreating provides sulfur removal to meet product specifications and/or to allow for processing higher sulfur crudes.
Table 2.3 Refining configurations and their yields

<table>
<thead>
<tr>
<th>Configuration group and process technologies</th>
<th>Product and yield (vol %)</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Topping                                     | 2 32 30 37               | • Product sulfur levels similar to crude’s sulfur.  
                                              |                           | • Distillate contains lots of heavy products  
                                              |                           | • Gasoline has low octane value             |
| Hydroskimming                               | 3 28 30 37               | • Allows refiners to adjust product slate  
                                              |                           | • Provides new possibilities to improve  
                                              |                           | fuel quality, especially for gasoline      |
| Conversion                                  | 3 49 30 17               | • Allows high yield of gasoline and distillate |
| Deep Conv/Complex                           | 3 47 43 4               | • Addition of coking allows minimal  
                                              |                           | production of low valued fuel oil          |


As in the case of the topping refinery the yield of products is  
entirely dependent on the crude oil feed. In the hydroprocessing  
configuration, gasoline can be produced in place of naphtha and  
fuel sulfur quality can be adjusted.  
The topping or hydroskimming refining capability is significantly  
enhanced under the **conversion configuration**. This configuration  
adds cracking and/or hydrocracking capacity. The addition of  
conversion facilities allows the refiner to adjust refined product  
yields to match product demand. The actual yield can vary  
significantly depending on the type

![Figure 2.3 Topping configuration with typical yields](image-url)
and capacity of the conversion capacity employed. Figure 2.5 illustrates conversion configuration yield with average crude quality, a relatively high level of heavy oil processing, and a mix of catalytic cracking and hydrocracking capacity.

The conversion operations are central to the economics of the refinery because of the high yield of gasoline and distillate and the ability to adjust feed types and product yields. The natural yield of light products (gasoline, and distillates) from crude falls short of market demands and the increment must be made up through conversion operations. The light products generate a price premium based on overall product supply and demand and the cost (operating and capital) of the incremental conversion processing.

With the final deep conversion (complex) configuration, as illustrated in figure 2.6, product yields can be adjusted beyond that of the conversion configuration. Specifically, the addition of coking allows for minimal production of lower value heavy fuel oil, most being converted through coking and subsequent processing, to gasoline and distillate products.

**What are the different refining process technologies?**

Refineries are comprised of a number of individual technology based processing facilities with varying objectives, and integrated as necessary to meet product targets. The types, size, number and flow sequence of a specific refinery (i.e., refinery configuration) will vary depending on crude oil quality, required product mix and quality, and environmental, safety, economic or other constraints. The major refinery processing steps or technologies can be categorized into six functional areas: separation, conversion or cracking, combination, reformulation, treating and other specialty or support operations. All these steps and technologies are included in figure 2.7 that illustrates a complex refinery configuration.
gasoline intermediates, jet fuel and diesel.

**Coking** is a thermal, non-catalytic process that cracks the heaviest residue from crude distillation into a full range of lighter intermediates for further processing. The cracked products consist of light gases and low quality gasoline and distillates and gas oils which are further processed into final product.

Coking provides the refining system with the final means of converting the heaviest portion of the crude into useful lighter products. While a relatively small volume of the residue can be processed in other catalytic conversion facilities, such processing is limited due to the level of contaminants in the heavy residual feed and the resulting yield economics.

**COMBINATION**

Combination processes, as listed in table 2.4, link two light gaseous streams together to form a larger higher valued fuel product. At least one of the gas streams used in the combination process is a reactive olefin hydrocarbon molecule produced via fluid catalytic cracking, coking or outside petrochemical operation. The major combination processes are alkylation, etherealication and polymerization.

**Alkylation** combines the lighter FCC products (olefins, usually butylene or a mixture of butylenes and propylene, with a non-olefin) to produce a higher octane gasoline stream. The olefin and isobutane are reacted in the presence of a strong liquid acid and the final products separated in a fractionation section. There are two conventional alkylation processes that are differentiated by the type of acid catalyst used, hydrofluoric acid (HF) or sulfuric acid (H2SO4).

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**Table 2.4 Summary of separation and conversion/cracking technologies**

<table>
<thead>
<tr>
<th>Process technology</th>
<th>Typical products slates</th>
<th>Typical product characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SEPARATION TECHNOLOGIES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude distillation</td>
<td>Separates crude oil into products: Light gas, refinery fuel, light and heavy naphtha, distillates, gas oils, bottoms or residue.</td>
<td>Oldest available technology forms the heart of any refinery and determines the capacity of the refinery. Products typically are low valued with sulfur content similar to the crude processed and product needs to be further refined to meet today’s specifications.</td>
</tr>
<tr>
<td><strong>CONVERSION/CRACKING TECHNOLOGIES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC, fluid catalytic cracking</td>
<td>Breaks (cracks) heavy (large) oil molecules into lighter (smaller) more valuable molecules like LPG, Gasoline (50-60%), Distillate, Light olefins for chemical processing, heavy oil. Products often optimized for petrochemical feedstocks.</td>
<td>Increases product value from the Crude Unit. Products, unless treated, still contains similar quantities of sulfur as from the crude. Untreated FCC products are main source of sulfur for gasoline.</td>
</tr>
<tr>
<td>Hydrocracking</td>
<td>Breaks (cracks) heavy (large) oil molecules into all gasoline and/or jet and diesel and reduces sulfur and aromatic content by hydrotreating.</td>
<td>Provides high valued lighter products with low sulfur and aromatic content. Investment value for such units is significantly higher than FCC units.</td>
</tr>
<tr>
<td>Coking</td>
<td>Breaks (cracks) the heaviest oil molecules from the crude unit into low valued gasoline, distillates and gas oil.</td>
<td>Upgrades heaviest most low valued stream from crude into lighter products still containing high concentrations of metals and sulfur.</td>
</tr>
</tbody>
</table>

Both alkylation processes pose potential environmental and public health concerns. With HF concern centres on possible release of a toxic vapour cloud that could harm refinery workers and the public. H2 SO4 is less hazardous than HF, but presents handling, storage, and transportation concerns.

**Etherification** combines lighter products from FCC unit (various light olefins) with alcohols (methanol, ethanol) through a low temperature and pressure process resulting in an oxygenated compound called ether, such as methyl tertiary butyl ether (MTBE), ethyl tertiary butyl ether (ETBE) and tertiary amyl methyl ether (TAME). The process employs a solid catalyst system. The most common ether, MTBE, is a gasoline component with high octane number and other characteristics valuable in clean gasoline production. It is the primary source of gasoline oxygen required in clean gasoline regulations.

**Polymerization** combines two light olefins, also to produce a high octane gasoline component. The process employs a fixed catalyst bed at low temperatures and pressure. The process is relatively inexpensive, the product is less desirable than alkylate or ether. Polymerization product consists primarily of olefins that are unstable in gasoline (gum forming).

**REFORMULATION**
Reformulation processes, as listed in table 2.5, alter the chemical composition of hydrocarbons in refinery intermediate streams in such a way as to enhance the performance characteristics of the final fuel. The primary reformulation processes are catalytic reforming and isomerisation, both of which are widely used to increase the octane of gasoline blending components.

**Catalytic reforming** is used to upgrade low octane gasoline boiling streams (naphthas) to high octane blending streams. There are a number of chemical reactions in the reforming process, but the primary reactions involve production and/or rearrangement of compounds characterized as aromatics. Aromatics are ring shaped molecules that exhibit high octane characteristics and in pure forms constitute valuable feedstocks for the petrochemical industry. The aromatics can be extracted in a separate process for petrochemical use.

### Table 2.5 Summary of separation technologies

<table>
<thead>
<tr>
<th>Process technology</th>
<th>Typical products slates</th>
<th>Typical product characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMBINATION TECHNOLOGIES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkylation</td>
<td>Combines FCC low octane reactive molecules (olefins) with a less reactive light component to produce high valued, high octane, gasoline component.</td>
<td>Increases octane yield over either HF or H2 SO4 catalysts.</td>
</tr>
<tr>
<td>Etherification</td>
<td>Combines FCC reactive olefins with alcohols (i.e. methanol, ethanol).</td>
<td>Produces MTBE, ETBE are high octane clean gasoline components.</td>
</tr>
<tr>
<td>Polymerization</td>
<td>Combines two light olefins into high octane gasoline component.</td>
<td>Improves gasoline yield and octane number. Although process is relatively inexpensive the products typically have lower octane value than products from etherification or alkylation units.</td>
</tr>
</tbody>
</table>

Catalytic reforming has traditionally been the primary octane generator and control process for most gasoline oriented refineries. It is capable of producing a gasoline stream at over 100 octane and can vary product octane over a broad range with minor operating adjustments. However, the aromatic compounds produced and responsible for the higher octane, particularly benzene, have more recently been found to exhibit negative gasoline toxics characteristics. This has introduced pressure to seek lower aromatic octane sources.

Isomerisation involves chemical alteration of low octane (paraffin) hydrocarbon to higher octane formulations (isoparaffins). Isomerisation is also used (more recently) to reduce the benzene content of gasoline components as a toxic control measure.

TREATING
Treating processes involve the removal of undesired chemicals (i.e., sulfur, nitrogen, heavy metals) from refinery streams. The primary treating process is hydrotreating (also referred to as hydrodesulfurization and hydrorefining) that utilizes hydrogen to remove sulfur for meeting final fuel product specifications. It is used on a wide range of intermediate or final product feedstocks from naphtha to heavy residue. In the role of treating intermediates, it is used before reforming to protect the catalyst and before catalytic cracking to reduce regeneration sulfur emissions, eliminate nitrogen and metal contaminants, reduce product sulfur and improve cracking yields. On the product side, it is used to meet final product sulfur specifications for gasoline, jet fuel and distillates. Hydrotreating can also be used to modify other product characteristics (i.e., diesel cetane or lubricating oil properties) to improve fuel quality.

Other treating processes such as Merox are used to eliminate specific sulfur molecules from final gasoline and jet fuel products. In addition, newer sulfur reduction technologies are being introduced to remove sulfur from fuels without requiring the hydrotreating process.

SPECIALTY AND SUPPORT OPERATIONS
There are a number of miscellaneous processing facilities of varying complexity and purpose required to support the refinery operation, produce specialty products (lubricants, asphalt, etc.) and to provide for environmental control. Outside of specialty product facilities, major support facilities include hydrogen systems, sulfur recovery facilities, light gas handling, product blending, utilities (steam, electricity and water) and wastewater treatment.

The final step in the refinery process is blending refinery streams into final products. In gasoline blending, an automated system meters and mixes blend stocks and additives. Properties are tested with online analyzers supplemented by laboratory facilities, and computer control is employed to adjust blends to target specifications. Blending of other products usually involves less analysis and does not employ computer control.

Steam and electricity are used in processing operations, for heating, and for pumping and compression energy. Refineries purchase utilities or generate them on-site. On-site generation involves steam boilers and traditional power generation facilities. Cogeneration is also used for optimizing refinery energy. Cogeneration refers to the efficient integrated production of electrical power and steam.

Petroleum refineries are very energy intensive and through the numerous processing storage and handling create the potential for emission of airborne pollutants, water contamination, and hazardous waste generation. Emissions are also generated through the combustion of fuels required to provide heat and utilities, and to regenerate catalysts.

Regional and national refinery makeup and capabilities in Asia
As indicated below in figure 2.7, the Asian Pacific region experienced a dramatic growth in oil product demand until the onset of the 1997/98 Asian economic crises. Like most parts of the world, demand growth in Asia is increasingly focused on gasoline and mid-distillate. The
Table 2.6 Summary of reformulation technologies

<table>
<thead>
<tr>
<th>Process technology</th>
<th>Typical products slates</th>
<th>Typical product characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic reforming</td>
<td>Rearranges low valued, low octane naphthenes and paraffins, gasoline components into higher valued, higher-octane aromatics.</td>
<td>Products have high octane value and typically high aromatics content less attractive for more advanced fuel formulation.</td>
</tr>
<tr>
<td>Isomerisation</td>
<td>Rearranges low valued, low octane normal paraffins into higher valued, higher octane, iso-paraffins.</td>
<td>Produces both environmentally (reduced olefin and benzene content) and economically high valued gasoline components.</td>
</tr>
<tr>
<td>Hydrotreating</td>
<td>Removes undesired chemicals (sulfur, nitrogen, heavy metals) from products.</td>
<td>Upgraded product quality of intermediate and final products.</td>
</tr>
</tbody>
</table>


Growth in travel is causing increased demand for jet fuel, gasoline and diesel at a time when there is a decreased demand for fuel oil.

As indicated in figure 2.8, in the 1990’s, refining responded to anticipated growth with aggressive capacity expansion. Refining capacity in China, India and South Korea more than doubled during this period. In the early 70’s the regions refining industry became dependent on crude imports. With further anticipated growth in product demand, the region will grow increasingly more dependent on imported crude and refined products and struggle with investments required to implement clean fuel legislation.

With the construction of refineries their configuration is determined by their local crude oil quality and their local demand.

Generally speaking, as seen in previous parts of this module, although Asian crudes also differ from source to source, they typically are waxier and contain less sulfur than crudes from other parts of the world. Many Asian refineries have been built to meet their large demand of fuel oil (large number of topping and hydroskimming refineries). When most Asian refineries were built, higher valued products, like gasoline, jet kerosene and diesel were secondary in the output slate, and little upgrading was available to increase production of these fuels.
As a result of rapid economic development, most Asian countries have experienced an increase in jet fuel, diesel and gasoline consumption due to an increase in travel and use for transport, agriculture and power plants. As is the case in many parts of the world, Asia is experiencing a decline in fuel oil use and untreated crude oil that typically was their sources for power plants and boilers due to more stringent legislation in this area. Currently, Asia is the 2nd largest crude processing region in the world, after the U.S. and before the EU. Due to high economic growth, the region is increasingly requesting more transport fuels such as gasoline, jet and diesel as well as an increased demand for raw material for petrochemical production. As shown in figure 2.9, the main fuel required for Asia, overall, is distillate. Volumetric product requirements are more comparable with Europe than with the U.S. that always has been and is driven by the large gasoline consumption.

Not only is the Asian refining industry experiencing shortage in local crude supply having to look for new sources of different quality but also they are experiencing a large shift between products requested and their qualities.

Similarly, as illustrated in figure 2.10, for the Asian countries chosen for this training, diesel is the dominant transport fuel. Diesel represents 60 to 80 percent of the transportation demand for these countries as compared to slightly less than 60 percent for EU and less than 30 percent for the U.S.

Asia has 200 refineries representing the largest regional crude distillation capacity in the world. As the Asian refining sector has traditionally focused on the

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**Figure 2.9** Asian refining capacity from 1970 to 2002


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**Figure 2.10** Typical product slate in USA, Western Europe and Asia Pacific

production of fuel oil there are generally less gasoline upgrade units such as FCCs than in the U.S. Seen from the simple ratio of catalytic cracking capacity to crude capacity we see that Asia overall at only 14% is outpaced by the U.S. at 34%. However it is more similar to the EU’s capacity at 15%. As already discussed, this is partly because the Asian and European markets are driven by large diesel demand while the U.S. is driven by gasoline demand.

However the amount of available equipment also indicate the upgrade capacities available. There are large differences between the Asian countries and their refineries. As shown in table 2.4, in general Japan, S. Korea and Taiwan have a more sophisticated refining industry with relatively larger possibilities to upgrade the heavier fractions into lighter products. On the other hand, some Asian countries and several refineries only have topping refineries (Myanmar) with no upgrade capacities available, many countries and refineries are simple hydroskimmers with very limited upgrade capacities like for Bangladesh, Pakistan and Sri Lanka.

**Technical issues and costs related to refinery upgrades**

There is no single answer to what refinery upgrading will cost. Every refinery around the world is

### Table 2.7 Asian refining capacities (2002)

<table>
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Source: Oil and Gas Journal.
unique and it's operating, maintenance and investments costs depend on available processes and equipment, location, crude being processed, supply of catalysts, available capital and so forth. The only common driver among all refiners is economics. Every refinery aims to optimize their tools to run a profitable business. Any refinery investment is generally capital-intensive.

Profitability is effected by many factors for example local and global commodity markets including competition, regulatory restrictions, pricing of imports of raw material and products, capacity utilization and capital expenditures. Also, today to a large extent, investment in clean fuels technology is being forced by legislation. Investment has been driven by a desire to survive in the market, rather than to boost profitability. In such situation, it is not surprising to find that refiners have generally seen negative returns from related investment.

There is a broad range of possible modifications and additions to existing refineries to meet emerging automotive fuel specifications including the following:

- Introducing operating changes to available technology.
- Changing the crude oil supplied to the refinery.
- Modifying the fractionation process(es).
- Introducing new processing facilities.
- Increased and optimized use of utilities including hydrogen, energy etc.
- Changing the catalyst used and/or its quantity.
- Upgrade of existing facilities to enable the handling of higher specification products.
- Upgrade and exchange equipment (pipelines, valves, tanks etc) make them resistant (corrosion, erosion etc) against new product qualities.

Refinery modification strategies are always project-specific and linked to desired objectives. A multi pronged program including reduced or eliminated lead, limited benzene and aromatic levels, RVP control, front-end octane improvement, and sulfur reduction could include many new process options while a more modest program might need only a few of those options. The increased investment costs and operating costs of even a modest reformulation program might be substantial, in some instances changes could even be an unsustainable combination.

In summary, it is difficult, even impossible, to give guidelines on costs and cost-effectiveness of fuel modification, because refinery characteristics differ so widely. In fact any cost figures, which may be publicised are typically based on assumptions rather than facts. This is not only because of the time involved to make such calculations but also because typically the refining industry does not have any desire to provide detailed processing data to external public sources.

However, whilst keeping this in mind, the following section gives an overview of existing studies on refinery investment costs for lead phase out, isolated sulfur reductions and overall clean fuels supply:

**REFINERY COSTS IMPLICATIONS FROM LEAD PHASE OUT**

In several studies (Abt Associates, 1996, Thomas, 1995, Hirshfeld and Kolb, 1995a and 1995b), the typical cost of phasing out leaded gasoline – including the annualized refinery investment costs amortized over the life of the investment, the incremental operating costs of producing gasoline without lead, and/or the costs of gasoline additives – has been estimated in the range of US$ 0.01 – 0.02 per litre. The cost difference between the productions of leaded (0.15g/l) and unleaded gasoline in Germany, for example, was estimated at US$ 0.01 per litre. Even in technologically less developed skimming refineries, the cost of total phase out of leaded gasoline has been estimated under US$0.03 per litre (Hirshfeld and Kolb, 1995a).

Again, we need to highlight that each refinery has a unique technical structure and set of alternatives to replace lead, and the costs of required investments and technical measures necessary to support the phase-out of lead should be evaluated on a case-by-case basis.
REFINERY IMPLICATIONS FROM DECREASED SULFUR DEMAND

The process requirements and costs needed to reduce diesel from relatively high (i.e. 2,000 ppm) to ultra low sulfur levels (around 10 ppm), such as other changes in refinery production and objectives, depend on the specific refinery crude and product slate and refinery configuration. The process requirements may necessitate installation of a number of new state-of-the-art processing facilities added to the existing refinery facilities. Conversely, where some level of existing desulfurization exists, the requirements for the 10 ppm target may be limited to revamping of existing facilities to accommodate more severe operations.

In the simplest refining configuration, 2,000 ppm diesel can be produced through simple crude distillation (topping plant). A topping refinery using low sulfur crude oil can produce 2,000 ppm diesel without further processing. In this situation the sulfur can be reached by building a new, high severity desulfurization unit incorporating the latest technologies (catalyst, hydrogen clean-up and purification, etc.) A new unit can be designed to process the diesel to 10 ppm.

In other situations, the refiner may already have desulfurization facilities in place, but the desulfurization is not adequate to meet a 10-ppm sulfur target. In many of these cases, the existing desulfurizer can be modernized/revamped to accommodate higher severity operations and produce 10-ppm quality product. The revamps typically include such things as the latest high active catalyst, changes to the internals of the reactor vessels, addition of a reactor providing for additional catalyst volume, and new or upgrade of hydrogen stream treating and purification facilities. Adjustments in operations can also in some cases be used to aid in production of the lower product sulfur (higher temperatures and shorter lengths of time on stream between required shutdowns).

The extent of modification required for the modernization/revamp depends again on the type and capabilities of the existing hardware and the processing environment. The revamp requirements are not simple, but can provide facilities for meeting 10 ppm product at much lower cost than a new unit (on the order of half the capital cost). The revamp option is not economical for all refining circumstances.

The only way to provide any cost estimate of refinery changes is to do so on a refinery specific basis. All other studies tend to generalize refineries and situations, investment possibilities, availability of raw material etc. and can only provide indicative values. Also, the requested investment of technologies might change, when looking at past studies emerging technologies tend to become less capital intensive over time, product market changes etc. For example the costs of achieving low-sulfur levels depend primarily on the current state of refining equipment being used. However, once the initial investment is made for refinery upgrades there may be relatively little price difference as sulfur levels decline, even to low and near-zero levels.

The many quoted incremental costs for near-zero sulfur diesel refining range from 0.3-2.8 cents per litre, although most estimates appear to fall in the range of 0.5-1.5 cents per litre. As made from the European market, real-world experience has confirmed this lower range of costs. Many countries (note not refineries), like Belgium, Denmark, Finland, Germany among others only gets 50 ppm sulfur fuels to their markets after providing a 1.5 – 3.84 cents/litre tax cut.

The following section highlights some recent refining related cost studies starting with the most recent:

COST OF DIESEL FUEL DESULFURIZATION IN ASIA

January 2003, Enstrat International Limited

This study, Costs of Diesel Fuel Desulfurization for Different Refinery Structures Typical of the Asian Refining Industry, includes 12 Asian countries with different refining capacity and demand as well as varying degrees of current refinery investment and capacity to produce reduced sulfur diesel.
After several simplifications such as the cost to include sulfur reduction of the entire diesel pool and holding the diesel demand static. This ADB study estimates that costs associated with lowering sulfur levels in diesel fuel are roughly constant, at around 1.1 cents per litre, for product levels ranging from 3,000 to 250 ppm sulfur. There is a gap in sulfur levels considered, from 250 to 50 ppm, over which costs more than double. At around 2.7 cents per litre, costs are again roughly constant for 10 ppm and 50 ppm sulfur diesel fuel, increasing by less than 1% to up to 9%, depending upon the country.

In exploring the price gap between 250 and 50ppm sulfur, this study finds that investment in hydrocracking capacity is the least costly alternative for achieving the lowest sulfur limits, whereas all higher limits were achieved with hydrotreating units using varying pressures. For each case, above and below 250 ppm, the study finds that investing directly in more efficient technology from the outset is less costly than moving through a range of intermediate technologies. The study states, “[these findings] reinforce the desirability of avoiding intermediate sulfur specification levels, which may be achieved through the deployment of relatively less advanced refining technologies, which may become ineffective or partly obsolete if subsequently stricter sulfur limits are going to be mandated” (Enstrat 2003).

ULTRA LOW SULFUR GASOLINE AND DIESEL REFINING STUDY (2000)
This study, ULS Gasoline and Diesel Refining, assessed the costs of lowering fuel sulfur levels from a maximum of 50 ppm to a maximum of 10 ppm in Europe. The study, which again contains many assumption (only FCC refineries, no octane loss, low sulfur level in crude etc) found costs to achieve near-zero sulfur per liter) under the EURO 5 scenario. Gasoline costs were around 1.5 cents per gallon (0.40 cents per liter) across the board. In general, the results showed some cost savings when China’s major metropolitan areas went to the new specifications first and rural areas followed, but the differences were not huge.

In summary, the study noted that the Chinese refining industry had already undergone a major build-up program, and additional investments are continually taking place. Yet the investments made will not be sufficient to allow the industry to meet demand for higher-quality EURO fuels. Technologically, it is possible for Chinese refiners to produce EURO standard fuels, yet economically and logistically it will yet prove a challenge. For example, building a million barrel per day of heavy feed hydroprocessing would be an Herculean labour by any standard, and the total equipment capital costs in the scenarios of 2010 were calculated at around US$2.3 million per day.

IMPROVING TRANSPORT FUEL QUALITY IN CHINA
The intent of this study was to explore China’s refining options in light of changing gasoline and diesel fuel specifications.
A key hypothesis of this study was that, although Chinese refining has expanded enormously and has many plans on the books for continued investment, the current and planned refinery configuration would be insufficient to meet growing domestic demand for EURO-style fuels. To test this hypothesis, the team built and employed a linear program model of the Chinese refining sector and used scenario analysis to test the ability of the Chinese refining sector to produce fuels of EURO 2, 3, 4 and 5 standards in 2005, 2008 and 2010. Twelve scenarios were developed which varied by year, fuel quality and fuel volume. The model was given the option of building refinery technologies to meet the specifications, with input in Chinese demand by fuel type and Chinese capital costs provided by CPCC.
The study allocated capital costs to gasoline and diesel, and calculated that reformulating diesel in the year 2010 would add around 3.2 cents per gallon (0.85 cents per liter) capital cost to the refining sector, rising to around 3.7 cents per gallon (0.98 cents
levels were much lower once initial reductions to 50 ppm had been made. Incremental costs were expected to range from 0.3-0.5 cents per litre in Northern Europe and 0.5-0.7 cents per litre in Southern Europe.

**ULTRA LOW SULFUR STUDIES BY THE EPA AND OTHER SOURCES**


In 2000, U.S. EPA proposed a 15 ppm sulfur limit for highway diesel fuel, reduced from the current cap of 500 ppm. EPA used a refinery-by-refinery approach to estimate the incremental and capital costs of the new ruling. Costs of the new standard were predicted to start at a national average of 1.0 cents per litre and increase to 1.1 cents per litre in 2010. U.S. aggregate capital costs in 2010 were expected to be around $5.3 billion (EPA 2000).

Other cost studies were undertaken and submitted as part of the rulemaking. In general, the studies include EPA's estimates for incremental costs within their range, although many include alternate scenarios with higher estimates. Capital cost estimates are both higher and lower than EPA but generally relatively close.

In October 1999, a MathPro study, Refining Economics of diesel sulfur standards, analyses the refining economics controlling the sulfur content of diesel fuel (both on-highway and off-highway) to low limits. The objective was to estimate the average incremental cost, investment requirements, and technical implications of reducing the sulfur content of diesel fuel meet various specified standards. This analysis represents refiners achieving diesel fuel sulfur control using commercial desulfurization technology: severe conventional hydrotreating.

The study provides the estimated average cost, annual cost and investment requirements for many different cases. The per gallon costs of desulfurization standards ranges from 2.6 – 8 cents per gallon dependent on sulfur level and refinery configurations. The related annual costs ranges from $1,000 million to $3,500 million.

A study commissioned by the Engine Manufacturers Association, used a linear programming model to evaluate several final sulfur endpoints for both on-road and off-road diesel fuel. The study estimated that a 15 ppm cap for highway diesel only would increase costs by approximately 0.8-1.4 cents per litre (MathPro 2000). Capital costs ranged from $3.4 to 6.1 billion, with a figure of $3.9 billion estimated to match the EPA assumption of 80% revamp and 20% new units (EPA 2000). In response to the EPA proposal to extend the 15 ppm sulfur cap to nonroad diesel fuels a supplement to the original MathPro study included a 15 ppm cap for all diesel fuel. The extension of the 15 ppm sulfur cap to non-road diesel was expected to raise the estimated range of incremental costs to 1.2-2.0 cents per litre (MathPro 2000). In all of these estimates, the high values appear to reflect a less realistic approach to refinery upgrades that allows for less flexibility and does not provide the option of retrofitting existing units.

An Ensys study commissioned by the Department of Energy in the U.S. found results based upon either conservative or optimistic technology assumptions. EPA (2000) reported that DOE's conservative technology assumption included only commercially available technologies and resulted in higher costs of U.S. .3-1.6 cents per litre. The optimistic technology scenario appears to have used assumptions more similar to EPA and resulted in incremental cost values very similar to EPA, 1.1-1.2 cents per litre. The full range of capital costs reported was $2.7-6.5 billion, and under assumptions similar to EPA's conservative scenario predicted $4.4 billion and the optimistic scenario $3.1 billion (EPA 2000).

After the standards were proposed, the Energy Information Administration (EIA) undertook a study at the request of the Committee of Science, U.S. House of Representatives. Using a modelling approach, EIA reported an initial range of 1.2-1.9 cents per litre, rising to 1.7-2.4 cents per litre after 2010, with total costs ranging from $6.3-9.3 billion (EIA 2001). EIA also reported on a study done by Argonne National Labs, which found a similar range of
incremental costs, 1-2 cents per liter, but even higher capital costs of $8.1-13.2 billion (EIA 2001).

Studies commissioned by the American Petroleum Institute (API) and the National Petroleum Council (NPC) provided different estimates and tended towards higher incremental costs, although they fell within the ranges reported by other studies. A study by Charles River Associated, Inc. and Baker and O’Brien, Inc., commissioned by API, predicted the average cost to produce 7 ppm sulfur diesel (in order to meet the 15 ppm cap) from 500 ppm sulfur diesel to be 1.8 cents per litre. The capital investment predicted was $7.7 billion (EIA 2001). The NPC estimated an incremental cost of 1.6 cents per litre for 30 ppm sulfur diesel, with an investment of $4.1 billion (EIA 2001).

REFINERY IMPLICATIONS FROM OVERALL ASIAN IMPROVED FUEL QUALITIES

Clean Transportation Fuels Supply Security Study, EWG02/2001T, by Hart Downstream Energy Services

The objectives of this study were to follow-up on a previously conducted analysis (the role of petroleum based and alternative transport fuels in reducing emission in the APEC Region) that had examined motor fuel quality enhancements necessary to improve air quality in Asia pacific Economic Cooperation member economies. This study aimed to gain an appreciation of the supply impacts that several specification scenarios are likely to have on the region over the coming 10-year period. Study is not yet in public domain – is this the APEC study? Has this been released yet?

COST-BENEFIT ANALYSES OF NEAR-ZERO SULFUR DIESEL

Cost-benefit analyses in the U.S. and Europe have consistently found that the benefits of reducing sulfur in transportation fuels far outweigh the costs, regardless of the very different assumptions used. The U.S. EPA (Regulatory Impact Analysis, Control of Emissions of Air Pollution from Highway Heavy Duty Engines, EPA, July 2000) found the benefits of stricter fuel and emissions standards for diesel to be roughly 16 times higher than the increase in refining and vehicle costs required. In Europe (Umweltsbundesamt, July 2003, Future Diesel), the analysis investigated only the shift in sulfur levels, assuming new emissions standards were not contingent on sulfur standards. Air quality played a less important role in this analysis, which focused more on increased fuel economy resulting from design modifications made possible with near-zero sulfur fuels.

EPA performed a cost-benefit analyses for the Heavy-duty Engine and Vehicle Standards, assuming that near-zero sulfur diesel was integral to meeting the new emissions standards and thus in achieving the expected benefits. Reduction in premature mortality due to reduced PM levels was the dominant benefit. Additional benefits included reduction in health impacts (such as chronic bronchitis), visibility impairments, and crop damage. The predicted benefits totalled $70.4 billion, with predicted costs of $4.3 billion and a net benefit of $66.1 billion by the year 2030 (EPA 2000). Also it was estimated that the new regulations save 8,300 premature deaths, 750,000 respiratory illness and 1.5 million lost workdays.

Several aspects of the EPA analysis, including the timeframe, introduced considerable uncertainty into the final numbers. Yet, because many benefits were not monetized, one can still assume that the final numbers are an underestimate of the total benefits. In fact, a plausible alternative to EPA’s analysis based on the Krewski-Harvard Six Cities study found a more than 150% increase in total benefits, resulting in a net benefit of $177 billion (EPA 2000).

In contrast, the analysis performed by the Directorate-General Environment (2001) of the European Union looked only at the shift from 50 to 10 ppm sulfur fuels, assuming all vehicle emissions standards remained constant. In this context the primary benefit was increased fuel economy of new models taking advantage of near-zero sulfur fuel to achieve modest 2-3% increases in fuel efficiency. Gasoline and diesel fuels were considered together, with diesel expected to achieve
Recognizing the fact that the oil industry is one of the major contributors to the over-all sources of pollution in the urban area due to the available quality of fuel, the Clean Air Initiative for Asian Cities initiated a dialogue with the major international oil companies operating in the region and the major national oil companies in each country.

The objective of the meeting was to establish a dialogue between the oil industry and the Clean Air Initiative for Asian Cities (CAI-Asia) for the production and distribution of cleaner fuels in Asia.

The meeting was launched on July 2003 in Singapore and was attended by representatives from 12 oil companies, (Bangchak Petroleum Public Company, BP, Chevron Texaco, Exxon Mobil, Indian Oil Corporation, Pakistan State Oil, Petron Corporation, PTT Public Company Ltd., Shell, Showa Shell Sekiyu K.K., Singapore Petroleum Company and Thai Oil Company Ltd.) the Chairperson and representatives from the CAI-Asia Secretariat.

The dialogue resulted in the adoption of the “Singapore Statement” as given below:

"Singapore Statement"

We, the oil companies, that produce and/or provide oil products for the Asian market, which have gathered here in Singapore for the purpose of discussing cleaner air in Asia, share the concerns that air pollution is a serious developmental problem and that for Asia to develop further it is important that citizens are able to enjoy air of a quality which, by recognized standards, such as those recommended by the World Health Organization, should not cause them harm.

Air quality is impacted by emissions from a number of varied sources but we recognize that the rapid growth in mobility in Asia has contributed to an increase in emissions in many cities, and that the expected continued growth in number of vehicles will further add to the problem. Countries and cities in Asia experience different levels and types of air pollution, and actions taken to reduce air pollution need to take this into consideration. Any action taken to address air pollution should be based on sound science.

To enable ambient air quality in Asian cities to meet appropriate standards will require the identification and implementation of location- and context-specific initiatives, which are based on sound science and which recognize the necessary balance between economic, environmental, and societal needs and impacts. In this regard, we believe it is appropriate that a range of solutions be considered with the aim of identifying those which leads to the most balanced, cost-effective initiatives involving an acceptable overall cost to society, government and the stakeholders.

We are committed to working with key stakeholders, including governments, academia, civil society, and equipment/vehicle manufacturers to contribute to the identification of sources of pollution, as well as the formulation of solutions, particularly those designed specifically to reduce emissions from mobile sources.

Fuel quality is one of four equally important enablers to reduce vehicle emissions, the others being cleaner engine technology, better vehicle and engine maintenance, and effective traffic management and transport planning schemes. All four of these need to be taken into account when considering optimum, sustained solutions, the implementation of which will require integrated measures from a number of stakeholders.

We, the oil companies, appreciate the role taken by the Clean Air Initiative for Asian Cities (CAI-Asia) to initiate a dialogue among oil companies in Asia, and we express our full support for the goal of the dialogue: “To contribute to better air quality management in Asia.”

The dialogue on cleaner fuels in Asia is a significant contribution towards the objectives of the Partnership for Clean Fuels and Vehicles, which was set up at the World Summit on Sustainable Development (WSSD) in Johannesburg in September 2002 by a group of committed partners from governments, international organizations, industry, and non-governmental organizations (NGOs).

This global partnership intends to help reduce vehicular air pollution in developing countries through the promotion of clean fuels and vehicles, and will focus initially on two priority areas (i) the elimination of lead in gasoline and the phase down of sulfur in diesel and gasoline fuels, concurrent with, (ii) the adoption of cleaner vehicle technologies.

The active commitment and support of the auto industry to the Dialogue process will be vital for its success.

**Module 2**

**Case study 6** Phase out of leaded gasoline and delayed decision-making on investments

**Background** Indonesia represents a country that has a major refiner who has not invested in refinery upgrades over several years and is now resisting the complete introduction of lead free fuel and low sulfur fuel.

Detailed, independent specifications of fuels in Indonesia are not currently available.

**Issue focus** There has been a Ministerial Decree that requires nationwide ULG by Jan. 2003. PERTAMINA and the Ministry of Energy and Mineral Resources (which issued the ULG Decree) announced however at the US-AEP/USEPA seminar in June 2002 that they will not be able to fulfil the requirements of the Decree, and the soonest they plan to supply ULG outside Jakarta is 2005.

Ministry of Energy recently proposed to the Ministry of Environment that the Decree be revised, pushing the date back to Dec. 31, 2004. Given the delays accompanying finance deals for refinery modifications, it seems that even by this date the refinery modifications are unlikely to be complete.

It should be noted that there is number of non-governmental organizations based in Indonesia that are actively campaigning against lead. They held a number of informational meetings and workshops and have been engaged in educating the public and the legislature on the benefits of unleaded gasoline. Their objective is trying to create a public pressure to remove lead from gasoline.

The Ministry of Environment has been engaged in high-level talks in response to the Ministry of Energy proposal to change the Decree. The essence of the response is that the Decree should not be altered and Ministry of Energy and PERTAMINA must take an alternative approach to supply ULG (e.g. blend in another octane booster at the refineries as an "interim strategy" rather than just waiting several years until the refinery upgrades are complete). The concern is that the date will be pushed back again and again, as has already happened many times.

The reason for the delays given is that the absence of lead creates an octane deficit that can only be addressed by investing in refinery infrastructure. It has been argued that the economic situation in Indonesia does not allow significant capital investments.

The price of gasoline used to be lower than international market price, but last year Indonesian gasoline prices rose to very near the Singapore Platts price. The price is still at that level, despite the fact that the quality of gasoline remains markedly worse than that of Singapore. While the supply of unleaded gasoline to the capital city, which began in July 2001, is a big step forward for cleaner fuel (ambient lead concentrations have reduced since one year ago) the quality of the gasoline by both environmental and engine performance standards is not commensurate with its current price. Because unleaded gasoline is not supplied outside the Jakarta area (except Cirebon and Bali or a few isolated pumps), catalytic converters — which would make a big difference in vehicle emissions — cannot yet be phased in anywhere.

The result is that consumers are paying a high price but inhabitants are still saddled with heavy vehicle pollution. In Indonesia, leaded gasoline is still a serious public health and environmental issue.

The Ministry of Environment has recently decided to mandate Euro 2 emissions norms but the actual timing may be constrained by fuel quality.

Detailed, independent specifications of fuels in Indonesia are not currently available.

**Analysis/lessons learned**

- Analyze steps in phasing out lead in gasoline in the country
- The requirements for capital investments is an obstacle
- NGOs have been effective in educating the public in trying to create a public pressure to remove lead from gasoline

lower efficiency gains (2%) at higher costs (0.3-1.0 U.S. cents per litre) but with smaller increases in CO2 emissions from refineries. The reduction in pollutant emissions estimated from use of near-zero sulfur fuel in older vehicles was relatively minor, only a 5% reduction in PM for diesel vehicles.

Monetary benefits were predicted for seven different scenarios, ranging from a full introduction to a phase-in of near-zero sulfur fuel over the timeframe of 2005 to 2011, with the benefit analysis stretched out to 2020. The net present value of the benefits of the various scenarios (including both gasoline and diesel) ranged from $1.7 to $3.2 billion U.S. (Directorate-General Environment 2001).

While the analysis by the Directorate-General predicted only moderate air quality benefits from the incremental decrease in sulfur levels, the actual air quality benefits associated with reducing sulfur levels have been dramatic. A study in Denmark, one year after the level of sulfur in diesel fuel was reduced from 500 ppm to 50 ppm, revealed a significant decrease in ultra fine particle concentrations in the ambient air. The study related the drop in ambient concentrations to a 56% reduction in average particle emissions from diesel vehicles (Wåhlin et al. 2000).

These examples demonstrate that the benefits outweigh the costs of lowering the sulfur standards under a variety of assumptions. And benefits are even greater when sulfur levels are reduced from a higher baseline. The U.S. EPA, in comparing the heavy duty standards to past measures, found the cost-effectiveness to be in line with earlier regulatory efforts to strengthen emissions standards and reduce sulfur levels, although some past measures had been more cost-effective. At the same time, the European analysis demonstrates that the benefits, purely in terms of fuel costs, continue to be positive down to the level of near-zero sulfur fuels.

**Explanatory section—the automobile industry**

As discussed under Module 1, an integral part of the systems approach is automotive emissions and thus vehicle and aftertreatment technologies. As pointed out previously, many fuel components such as lead, sulfur, volatile compounds, heavy components etc. affect emissions control systems. Therefore, prior to setting a fuel quality strategy it is essential that a country analyses the characteristics of its vehicle fleet.

Changes in engine technology and emission control devices are typically driven by legislation and, in most cases, by countries with large automotive markets. If a country is constrained by domestic automobile production then it is likely to import vehicles with the same technology sophistication as from the exporting country. Therefore, the only manner in which to promote cleaner vehicles and new engine technology for domestic use is for domestic legislation to set strict standards for all vehicles produced inside or outside the country. This sends a clear signal to vehicle producers selling on the market and is increasingly seen as a positive rather than a negative development as due to economies of scale today’s global automotive producers find it more economical to produce one type of vehicle for several markets rather than tailor make vehicles for often smaller markets. In addition, as explained in the previous section it is then easier to voice their fuel quality demands for these vehicles.

To build on the previous Module, this Module, will now look in more detail at the fuel quality required to enable these different technology options and to optimise the efficiency of existing and new emission control systems.

**Engine emission control devices and engine technology options**

This chapter gives an overview of what automotive engine technologies and emission control devices are available, what they do, what emissions they control, and how are they affected by fuel composition?
After a brief introduction, specific information on the primary emission control devices will be given as follows:

- Name
- How does it function?
- What emissions are controlled?
- What fuel factors affect it's operation?

As seen above under figure 2.12 and the previous module, the automotive emissions of primary concern are HC, CO and NOx for gasoline engines and NOx and PM (particulate matter) for diesel engines. Control of these emissions to extremely low levels is now recognized to be a joint responsibility of the emission control hardware and the fuel to be used. It is important to recognize that modern emission control systems are combinations of many of the devices described. The newer systems are so complex that they require powerful on-board computers to control their operation.

Over the years, many studies have been conducted to determine the relationship between fuel quality and it's effect on emissions. Examples of these studies are US Auto/Oil, EPEFE and JCAP that are being explained in other modules.

Table 2.8 summarizes what automotive emission control devices are available, what emissions they control, and how are they affected by fuel composition. In summary, we see that gasoline car emissions are affected by many of the fuel parameters such as distillation, RVP, aromatics, olefins, sulfur while the main determining component for diesel emissions is sulfur.

Gasoline spark-ignition engines and emission controls

The first emission control on spark-ignition engines was in the early 1960’s in the United States when the crankcase positive ventilation valve (PCV) was installed. It was followed by rudimentary and then sophisticated controls on the engine combustion process, and then by the introduction of the unleaded gasoline/oxidation catalytic converter combination in the mid 1970’s. The carburettor gave way to fuel injectors in the early 1980’s, and computer-controlled engines with 3-way catalysts soon followed. Today’s modern vehicles mainly rely on very sophisticated engine controls, fuel metering systems, and 3-way catalysts with oxygen sensors. The current levels of emission control would not be possible without computer-controlled systems and the use of “clean” or reformulated gasoline.

Evaporative emission controls, which prevent escape of fuel vapours from carburettors, fuel tanks and refuelling, first started in the late 1960’s and early 1970’s. They have also become more sophisticated with time as the demand for lower and lower emissions has progressed.

**POSITIVE CRANKCASE VENTILATION (PCV) VALVE**

The valve is used to channel the crankcase blow-by gases into the engine intake system (to be burned as part of the intake change), instead of venting them to the atmosphere. The blow-by gases enter the crankcase after having passed by the engine piston rings during the combustion process. These gases contain unburned fuel and oil vapours.
Table 2.8  **Overview of emission control systems, their functions and fuel response**

<table>
<thead>
<tr>
<th>Emission control system</th>
<th>Emissions controlled</th>
<th>Fuel factors affecting operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GASOLINE SPARK—IGNITION ENGINES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive crankcase ventilation (PCV) valve</td>
<td>HC</td>
<td>—</td>
</tr>
<tr>
<td>Engine combustions controls</td>
<td>HC, CO, NOx, PM</td>
<td>RVP, distillation, aromatics and olefins</td>
</tr>
<tr>
<td>Evaporative emission controls</td>
<td>HC</td>
<td>RVP and front-end composition</td>
</tr>
<tr>
<td>Exhaust gas recirculation (EGR)</td>
<td>NOx</td>
<td>Minimum deposits required</td>
</tr>
<tr>
<td>Oxidation catalytic converter</td>
<td>HC, CO</td>
<td>Lead and phosphorus</td>
</tr>
<tr>
<td>3-way catalyst (TWC) and O2 sensor</td>
<td>HC, CO, NOx</td>
<td>Sulfur and silica compounds</td>
</tr>
<tr>
<td>Fuel Injection systems</td>
<td>HC, CO, NOx</td>
<td>Minimum deposits required</td>
</tr>
<tr>
<td>On-board computers</td>
<td>All</td>
<td>—</td>
</tr>
<tr>
<td>NOx storage traps/NOx absorber catalysts</td>
<td>CO2</td>
<td>Sulfur</td>
</tr>
<tr>
<td><strong>DIESEL COMPRESSION—IGNITION ENGINES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine combustions and fuel injector controls</td>
<td>HC, PM</td>
<td>—</td>
</tr>
<tr>
<td>Exhaust gas recirculation</td>
<td>NOx</td>
<td>—</td>
</tr>
<tr>
<td>Improved fuel injection systems</td>
<td>HC, NOx, PM</td>
<td>—</td>
</tr>
<tr>
<td>Oxidation catalytic converters</td>
<td>HC, CO</td>
<td>Sulfur</td>
</tr>
<tr>
<td>Particulate traps/filters</td>
<td>PM</td>
<td>Aromatics and distillation temperatures, sulfur</td>
</tr>
<tr>
<td>Lean NOx catalysts/NOx traps</td>
<td>NOx</td>
<td>Sulfur</td>
</tr>
<tr>
<td>Selective catalytic reduction</td>
<td>NOx</td>
<td>—</td>
</tr>
</tbody>
</table>


The PCV is a relatively low cost valve that eliminates emission of the HC rich gases in the crankcase. PCV can easily be adopted on the in-use- engines without such device. It is also important to note that fuel composition does not directly affect the PCV valve.

**ENGINE COMBUSTION CONTROLS**

Many engine operating factors, such as air-fuel (A/F) ratio and spark timing, influence the engine’s production of HC, CO, NOx and PM. Early studies led to lean A/F’s and retarded spark timing to reduce HC and CO emissions.

Gasoline’s physical properties and chemical composition greatly affect the engine’s production of emissions. Gasoline front-end volatility (Reid Vapour Pressure) has to be sufficiently high to allow quick engine starts, especially in cold weather. Cold start is a major contributor to HC and CO emissions. Distillation temperatures, especially T50 and T90, affect HC emissions. Aromatic and olefin concentrations are directly related to the reactivity of the exhaust hydrocarbons. Fuel deposit control additives are essential to keep intake systems, fuel metering systems and combustion chambers as clean as possible to reduce production of HC.

HC and CO emissions are reduced, but NOx emissions are increased, with lean A/F. In addition, retarded spark timing reduces HC and NOx, but decreases fuel economy.

**EVAPORATIVE EMISSION CONTROL SYSTEMS**

Gasoline is a very volatile liquid, and it will evaporate and cause HC emissions. In vehicles, gasoline can evaporate when the vehicle is operating, and when it is not. Evaporation can occur from the fuel metering system, from the fuel tank, and from leaks. Also, these vapour emissions can occur during refuelling when the liquid fuel displaces the vapours in the
tank. Evaporative emission control systems were developed in the late 1960’s and commercialized in the early 1970’s to capture these emissions. At this time, activated charcoal pellets were used in a canister to capture and store the HC emissions, which are purged from the canister and into the engine during its operation. Control of refuelling emissions can be done at the service station pump, as is the case in California and many cities in the United States.

Control of gasoline volatility (Reid Vapour Pressure) and front-end composition (mainly C4 and C5 hydrocarbons) are critical for reducing evaporative emissions and their contribution to atmospheric ozone. However, it is important to note that only HC emissions are reduced with evaporative control systems.

EXHAUST GAS RECIRCULATION (EGR) SYSTEM
Nitric oxide (NO) production is a function of engine combustion temperature. Already in the 1970’s, it was recognized that the engine controls then in use would not sufficiently reduce NOx emissions. Thus, the EGR system was developed to recycle engine exhaust gas to the intake charge, and thereby reduce combustion temperature and NOx production. Only NOx emissions are controlled with EGR.

Fuel does not directly effect EGR system operation. However, fuel related deposits have to be minimized to keep the EGR metering valve operating.

OXIDATION CATALYTIC CONVERTER/UNLEADED GASOLINE
In the late 1960’s and early 1970’s, it became apparent that engine controls alone would not meet the more stringent emission standards that would come into use in the United States in 1975. Thus, the oxidation catalytic converter was developed. It uses a precious metal, originally platinum, to enhance the reactions in the exhaust stream between HC and CO to produce CO₂ and water in this way, HC and CO emissions are reduced.

Lead in gasoline was quickly determined to be a major poison to oxidation catalysts, leading to the advent of unleaded gasoline. Although sulfur in gasoline was early on recognized as a poison, it was not as bad as lead, and efforts to reduce it were not fruitful until the 1990’s. Phosphorus was also recognized as a poison and phosphorus containing gasoline additives were eliminated. Phosphorus in engine oil was reduced.

THREE-WAY CATALYSTS AND OXYGEN SENSORS
As emission standards became progressively more stringent, and NOx reduction became more important, the need arose to reduce all three simultaneously in the exhaust system. Because of the chemistry involved, the engine had to operate at the stoichiometric A/F, allowing just enough O₂ to fully oxidize the carbon and hydrogen in the fuel, and an exhaust system sensor was needed to ensure that it did. Thus was developed in the late 1970’s and early 1980’s, the three-way catalyst, oxygen sensor system. Because it required tight A/F control, on-board computers would also be needed. This type of technology reduces HC, CO and NOx simultaneously.

As indicated in figure 2.13, it was subsequently determined that gasoline sulfur content

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**Figure 2.13 Sulfur influence on emission with TWC**

![Graph showing sulfur influence on emission with TWC](image)

adversely affected the performance of these systems. Also, gasoline contaminated with silica compounds can readily kill oxygen sensor operation and result in greatly increased emissions. The impact of these contaminants increases with more efficient and advanced catalytic controls.

FUEL INJECTION SYSTEMS
Carburettors had been used for many years to meter gasoline to the engine. However, they were very poor for precise metering, and they were subject to problems from build up of fuel-related deposits. Thus, in the late 1970's and early 1980's, fuel injection systems were developed to give more precise fuel metering (lower emissions, better fuel economy, and improved driveability and cold starting). Fuel injection systems were more readily controlled using on-board computers than carburettors. Initially, there were throttle-body fuel injection systems, whereby a single or two injectors were mounted in the normal carburettor position and injected fuel into the intake manifold. They were subsequently replaced in the middle 1980's with port-fuel injection (PFI) systems, which used an injector at each intake port. PFI provided very precise fuel metering. Fuel injection systems helped reduce HC, and provided some benefit on reducing CO and NOx.

The key fuel factor influencing these systems is the presence of good deposit control gasoline additives to prevent deposit formation in the small opening at the tip of each injector and on the intake valves and in their ports.

ON-BOARD COMPUTERS (ELECTRONIC CONTROL MODULE)
This is the heart of all modern emission control systems. The computer, in combination with a variety of sensors, is used to monitor and control all of the components of the emission control system, such as the engine's combustion settings, fuel metering, idle speed, oxygen sensor, three-way catalyst, evaporative emission controls, etc. Also, all On-Board Diagnostics of emission-related problems are monitored and stored in the computer.

All emissions are affected by the operation of the On-Board Computer. However, fuel has no direct impact on the On-Board Computer.

NOX STORAGE TRAPS/NOX ABSORPTION CATALYSTS
In order not to trade off higher fuel efficiency for increased pollutant emissions, lean-burn engines requires new after-treatment technology for the control of NOx. NOx storage traps are currently the most efficient NOx control technology available. These traps not only reduce NOX but also simultaneously reduce CO2. However, this technology is sensitive to sulfur hence recent demands from automotive manufacturers for 10 ppm sulfur fuels.

Diesel compression-ignition engines and emission controls
For many years, emission controls on diesel engines took a back seat to controls for gasoline engines. However, in the past 20 years or so, the emphasis on diesels has grown rapidly, and now they are receiving much more attention than gasoline engine emission controls, which are quite mature.

Compression-ignition (diesel) engines have been the backbone of the worldwide vehicle freight business for many years. Although many have advocated banning diesel engines because of their “harmful” emissions, this is unlikely to happen. Considering the tremendous improvements that have been made in reducing diesel emissions of NOx, particulates, smoke and odour, it is more likely that use of diesel engines will grow, especially in light-duty vehicles. Light-duty diesel engines have been a tremendous recent success in Europe. Although they cost more than the comparable spark-ignition engine, the buyer can make up the difference because of substantially better (25-30 percent) fuel economy.

For most of their duty cycle, diesel engines operate with considerable excess oxygen, resulting in generally low HC and CO emissions, and fairly high NOx emissions. However, during high-load conditions,
they operate close to stoichiometric, or even under oxygen-deficient conditions, and generate large emissions of NOx and PM. Thus, the critical emissions of concern are NOX and PM, and they are the most difficult to control to low levels.

Diesel fuel is much less volatile than gasoline. Thus, there is no need for evaporative emission control with diesel engines.

ENGINE COMBUSTION AND FUEL INJECTOR CONTROLS
Quite early on it was discovered that a significant reduction in HC emissions could be achieved by ensuring that diesel fuel injection nozzles had a positive shut off at the end of their injection phase. Improved fuel injector timing, aiming and spray patterns were also utilized. In this way, HC and PM emissions were reduced. Luckily, fuel did not play a significant role in the above.

EXHAUST GAS RECIRCULATION (EGR)
As with gasoline engines, EGR systems were developed for diesel engines to reduce NOx emissions. Again, fuel did not play a significant role.

IMPROVED FUEL INJECTION SYSTEMS
During the 1990’s, the emphasis on reducing diesel emissions grew, significant progress occurred in diesel engine combustion to reduce HC, NOx, and PM emissions. Key factors included: improved combustion chamber shape; improved fuel injection systems. The latter included: unit injectors; common fuel rails; higher injection pressures; fuel injection rate shaping; multiple injections during the combustion event. To make the above possible, on-board computers were introduced. These systems were capable of reducing HC, NOx and PM emissions. Luckily as in the case of the previous systems, Fuel composition and properties did not play a major role. However, pressure began to increase in Europe and the United States to reduce diesel fuel aromatic concentration and the top end distillation temperatures.

The U.S. auto manufacturers also began pushing for increased Cetane quality (from the low 40’s to above 50, as in the case in most of the rest of the world). The advent of low sulfur diesel fuel and increased fuel system pressures has resulted in the need for lubricity additives in the fuel to prevent pump and injector wear.

OXIDATION CATALYTIC CONVERTERS
These systems are similar to their gasoline counterparts. However, their task is more difficult because diesel engine exhaust is generally not as hot as that of gasoline engine exhaust. Such catalysts reduce HC and CO PM is also slightly reduced. In this case, diesel fuel sulfur content is the only parameter that impacts the catalyst.

PARTICULATE TRAPS/FILTERS (DPF, DIESEL PARTICULATE FILTER)
To date, achieving the extremely low levels of PM emissions required by the most stringent U.S., European and Japanese standards has not been achievable with the devices so far described. Thus, in the 1990’s, the development of particulate traps and filters accelerated. These devices, similar to catalytic converters, utilize a silicate

Figure 2.14  **Sulfur influence on PM filter technology**

substrate to essentially filter the carbonaceous particles from the diesel exhaust gas as it passes through. The systems would eventually “fill” with particles, causing an increase in exhaust system backpressure, and a loss of power. Thus, the systems have to be periodically regenerated by burning diesel fuel in the exhaust ahead of the trap. This increases exhaust gas temperature to a high enough level to combust the trapped particles. Control of this process is delicate and critical.

Today, several types are under development, including catalysed DPF (CDPF), continuously regenerating DPF (CR-DPF), microwave-regenerated DPF.

With the use of the particulate trap, PM emissions are reduced by up to 90%. Reduction of fuel aromatic content and lower top end distillation temperatures can reduce engine PM production, as can reduced fuel sulfur level.

**LEAN NOX CATALYSTS/NOX TRAPS**

Since one device has yet to be discovered that can simultaneously reduce diesel PM and NOx, special devices were explored for NOx reduction in the 1990’s. The two prime candidates, at least in the U. S., are lean NOx converters and lean NOx traps, each of which would be used in a systems approach along with an oxidation converter and a PM trap, making a very complex and costly system. The lean NOx converter requires a catalyst to react the NOx in the exhaust with a reductant, usually HC in the exhaust gas, to generate nitrogen and water. The NOx trap stores the exhaust NOx on a substrate. The NOx is periodically purged by running the engine under rich conditions to generate HC in the exhaust, which reduces the trapped NOx to nitrogen and water. The chemistry for both devices is “delicate” and still being improved.

For example, NOx is greatly reduced up to 90% for both gasoline and diesel, however, ammonia, NH₃, can be produced if the chemistry is upset. As in the case of gasoline, the NOx trap, is sensitive to sulfur as higher sulfur content poisons the lean NOx catalyst, requires more frequent regeneration of the NOx trap, and results in decreased fuel economy with both devices.

**SELECTIVE CATALYTIC REDUCTION (SCR)**

Because of the uncertainty regarding commercialization of lean NOx catalysts and NOx traps, SCR has been extensively explored, especially in Europe to meet stricter limits like set by Euro 4 and 5 heavy duty. SCR relies on use of a reductant, an aqueous solution of urea, added to the diesel exhaust gas, to reduce the NOx emissions. The primary issues with SCR are the availability and use of the urea solution, and avoiding what is called “ammonia slip” (the production of ammonia in the exhaust).

With SCR, NOx emissions are reduced, and the benefit of this technology is that fuel properties are not thought to affect SCR; however since it would have to be used in a system with an oxidation catalyst and a PM trap, diesel fuel sulfur content will have to be very low.

**EXHAUST PLASMA DEVICES**

Exhaust plasma devices have also received a great deal of attention in the past ten years to reduce NOx and PM. Some were thought to be sulfur insensitive. Although these devices may have promise, none have made it to production, and

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**Figure 2.15 Sulfur influence on NOx trap efficiency**

![Graph showing sulfur influence on NOx trap efficiency](image)

Source: Volkswagen.
interest may be waning. One possibility being explored for in-cylinder reduction of NOx and PM is Homogeneous Charge Compression Ignition (HCCI). This concept uses residual gases in the cylinder as ignition sources for the next combustion cycle. So far it has not been successful under all engine load and speed conditions. Fuel needs for this type of technology are still not fully known.

**Case study 7 The Indian example**

As part of the recent study conducted under the Indian Auto Fuels Policy different engine and emission technologies were selected as necessary to meet improved emissions limits. Together with such analysis they also included a cost analysis. The table below summarizes these very important findings. For more information refer to India’s Auto Fuel Policy.

**Table Internal combustion engine and emission control technologies for different emissions**

<table>
<thead>
<tr>
<th>Level of emission norms</th>
<th>Technology options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro I (India 2000)</td>
<td>Retarded injection timing</td>
</tr>
<tr>
<td></td>
<td>Open/re-entrant bowl</td>
</tr>
<tr>
<td></td>
<td>Intake exhaust and combustion optimisation</td>
</tr>
<tr>
<td></td>
<td>FIP-700-800 bar, low sac injector</td>
</tr>
<tr>
<td></td>
<td>High swirl</td>
</tr>
<tr>
<td></td>
<td>Naturally aspirated</td>
</tr>
<tr>
<td>Euro II / Bharat Stage II</td>
<td>Turbocharging</td>
</tr>
<tr>
<td></td>
<td>Injection pressure&gt;800 bar, moderate swirl</td>
</tr>
<tr>
<td></td>
<td>High pressure inline/rotary pumps, injection rate control</td>
</tr>
<tr>
<td></td>
<td>VO nozzles</td>
</tr>
<tr>
<td></td>
<td>Re-entrant combustion chamber</td>
</tr>
<tr>
<td></td>
<td>Lube oil consumption control</td>
</tr>
<tr>
<td></td>
<td>Inter-cooling (optional, depends on specific power)</td>
</tr>
<tr>
<td></td>
<td>EGR (may be required for high speed car engines)</td>
</tr>
<tr>
<td></td>
<td>Conversion to CNG with catalytic converter</td>
</tr>
<tr>
<td>Euro III / Bharat Stage III</td>
<td>Multi-valve</td>
</tr>
<tr>
<td></td>
<td>Low swirl – high injection pressure?120 bar</td>
</tr>
<tr>
<td></td>
<td>Rotary pumps, pilot injection rate shaping</td>
</tr>
<tr>
<td></td>
<td>Electric fuel injection</td>
</tr>
<tr>
<td></td>
<td>Critical lube oil consumption control</td>
</tr>
<tr>
<td></td>
<td>Variable geometry turbocharger (VGT)</td>
</tr>
<tr>
<td></td>
<td>Inter-cooling</td>
</tr>
<tr>
<td></td>
<td>Oxycat &amp; EGR</td>
</tr>
<tr>
<td></td>
<td>CNG/LPG</td>
</tr>
<tr>
<td></td>
<td>High specific power output</td>
</tr>
<tr>
<td>Euro IV / Bharat Stage IV</td>
<td>Particulate Trap</td>
</tr>
<tr>
<td></td>
<td>Nox Trap</td>
</tr>
<tr>
<td></td>
<td>On board dianostic system</td>
</tr>
<tr>
<td></td>
<td>Common rail injection - injection pressure&gt;1600</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell</td>
</tr>
<tr>
<td></td>
<td>CNG/LPG</td>
</tr>
</tbody>
</table>

Continues next page
## Technical Issues

Technical issues are important in the design of a medium term fuel quality strategy. If we speak about technical issues we can broadly divide them into: (i) issues related to the refineries that produce the fuel, (ii) the vehicles that use the fuel. The purpose of this exercise is to get an overview of what the most important technical issues are in your country with respect to these two areas. We expect that you will be able to make use of the information that we asked you to collect before coming to the training course in Sydney. Please

### Classroom Material

**Technical Issues**

<table>
<thead>
<tr>
<th>Level of emission norms</th>
<th>2-stroke</th>
<th>4-stroke</th>
<th>4-Stroke</th>
</tr>
</thead>
</table>
| **Euro I (India 2000)** | • Intake, exhaust, combustion optimisation  
• Catalytic converter | • 4-stroke engine technology | • Intake, exhaust, combustion optimisation  
• Carburetor optimisation |
| **Euro II / Bharat Stage II** | • Secondary air injection  
• Catalytic converter  
• CNG/LPG (3 wheelers only) | • Hot tube  
• Secondary air injection  
• CNG/LPG (3 wheelers only) | • Fuel injection  
• Catalytic converter  
• Fixed EGR  
• Multi-valve  
• CNG/LPG |
| **Euro III / Bharat Stage III** | • Fuel injection  
• Catalytic converter | • Fuel injection  
• Carburetor + catalytic converter | • Fuel injection + catalytic converter  
• Variable valve timing  
• Multi-valve  
• On-board diagnostics system  
• CNG/LPG |
| **Euro IV / Bharat Stage IV** | • To be developed | • Lean burn  
• Fuel injection + catalytic converter | • Direct cylinder injection  
• Multi-brick catalytic converter  
• On-board diagnostic system |

*Euro norms are not applicable for 2/3 wheelers in India.*

### Vehicle Technology Change

<table>
<thead>
<tr>
<th>Level of emission norms</th>
<th>2/3 wheelers</th>
<th>4 wheelers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trucks and buses (HCV)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bharat Stage II</td>
<td>Rs 1.25 lakh</td>
<td></td>
</tr>
<tr>
<td>Euro III</td>
<td>Rs 2.25 lakh</td>
<td></td>
</tr>
<tr>
<td>Euro IV</td>
<td>Rs 4.00 lakh plus</td>
<td></td>
</tr>
<tr>
<td><strong>Passenger cars</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro III</td>
<td>Rs 0.50 lakh</td>
<td></td>
</tr>
<tr>
<td>Euro IV</td>
<td>Not possible to predict now</td>
<td></td>
</tr>
<tr>
<td><strong>Two and three wheelers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro III</td>
<td>Rs 5,000–10,000</td>
<td></td>
</tr>
<tr>
<td>Euro IV</td>
<td>Not possible to predict now</td>
<td></td>
</tr>
</tbody>
</table>

*Source: Automotive Research Association of India (ARAI), August 2002.*
be aware that it is not intended in this exercise that you come up with the solution to the issues or problems that you identify.

**Detailed assignment**

Please try to complete the following overview. The best way to approach is to ask yourself the question: “what are the technical issues for refining in my country if I want to introduce cleaner gasoline or diesel?” or “What are the technical issues we will face with our vehicles if we want to reduce emissions from these vehicles by introducing cleaner gasoline or diesel?”

Upon completion of the exercise rank the technical issues in order of priority whereby 1 is the highest priority, 3 is medium priority and 5 is low priority. Select a person to present the results to the plenary. Good luck!

<table>
<thead>
<tr>
<th>Technical issues—refining</th>
<th>Why is this an issue?</th>
<th>Technical issues—vehicles</th>
<th>Why is this an issue?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td></td>
<td>Gasoline Vehicles</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>Diesel Vehicles</td>
<td></td>
</tr>
</tbody>
</table>

**For further reading**


Refinery Technology Online (RTOL) is an independent platform for sharing and exchange of technical information within the Oil Refinery Industry <http://www.r-t-o-l.com/index.php>

Oxygenated Fuels Association Website <http://www.cleanfuels.net/>


What is the U.S. Doing about MTBE and other Clean Fuels <http://www.acfa.ws/pp5.ppt>

Indian Auto Fuel Policy <http://www.autofuelpolicy.org/contents.htm>


**References**


Hirshfeld and Kolb, 1995a


Module: 2
Key Refining Technical and Cost Issues

Nicholas A. Costalias
Director, Refining Economics and Planning
Hart Downstream Energy Services

Fuel Quality Strategies Training Workshop

Agenda

• Refining Overview
• Key Refining Technologies
• Product Blending and Qualities
• Clean Fuels Refining
• Clean Fuels Costs
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 - Yield
Light & Heavy Crude Yield vs Product Demand

<table>
<thead>
<tr>
<th>Product</th>
<th>LPG</th>
<th>Gasoline</th>
<th>Distillates</th>
<th>Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lt Crude</td>
<td>10%</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>Hvy Crude</td>
<td>20%</td>
<td>50%</td>
<td>40%</td>
<td>10%</td>
</tr>
<tr>
<td>Products</td>
<td>30%</td>
<td>60%</td>
<td>50%</td>
<td>40%</td>
</tr>
</tbody>
</table>

Crude Oil Characteristics –Sulfur
Sweet vs Sour Crude

<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.
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
- 1\textsuperscript{st} stage - requires Diesel HDS
- 2\textsuperscript{nd} stage – aromatic saturation with noble catalysts
  - Process consumes high quantities of 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).

Asia Pacific, USA & W. Europe
% Upgrade Capabilities vs. Crude Capacity

Source: Oil & Gas Journal
Asian Countries
Upgrade Capabilities vs. Crude Capacity

Source: Oil & Gas Journal

Asia Pacific vs. USA & Western Europe Product Demand

Source: EIA, 2000
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>82</td>
<td>92 - 98</td>
<td>93</td>
<td>96</td>
<td>118</td>
</tr>
<tr>
<td>Benzene, vol%</td>
<td>1.2</td>
<td>0.2</td>
<td>5.5</td>
<td>.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Aromatics, vol%</td>
<td>2</td>
<td>0.2</td>
<td>65</td>
<td>26</td>
<td>0</td>
<td>0</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 MTBE/alcohol blending
  – Pricy. Availability issues

Clean Gasoline Quality Changes
Severe sulfur reduction

• Hydrotreat naphthas and FCC gasoline
  – Capital expenditure. Results in octane loss.

• Desulfurize FCC feed
  – High capital cost.
Clean Gasoline Quality Changes

Benzene reduction (toxics)

- Reduce benzene generators in reformer feed via fractionation
- Saturate (hydrogenate) benzene in light naphtha (new unit – capital cost)
- Isomerize light naphtha (new unit - capital cost)
- Extract benzene out of reformate. Sell it.
  - New unit, capital cost, loss of gasoline volume.

Clean Gasoline Quality Changes

Aromatics Reduction (toxics)

- Run reformer at lower severity
  - Octane loss, less hydrogen production

- Add diluents to gasoline pool (MTBE, alkylate).
  - Price and availability issues

- Extract, benzene, toluene, xylenes from reformate
  - New unit, capital cost, gasoline volume loss
Gasoline Sulfur Reduction Example

<table>
<thead>
<tr>
<th>Blend Stream</th>
<th>Vol Base</th>
<th>PPM S</th>
<th>Octane</th>
<th>Vol Low S</th>
<th>PPM S</th>
<th>Octane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lt Naphtha</td>
<td>6</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>16</td>
<td>600</td>
<td>86.5</td>
<td>2</td>
<td>600</td>
<td>86.5</td>
</tr>
<tr>
<td>Trt FCC Gasoline</td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>50</td>
<td>81</td>
</tr>
<tr>
<td>Isomerate</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>0</td>
<td>81</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>10</td>
<td>93</td>
<td>5</td>
<td>10</td>
<td>93</td>
</tr>
<tr>
<td>Total</td>
<td>48</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>PNAs, 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>
Clean Diesel Quality Changes

<table>
<thead>
<tr>
<th>Quality Change</th>
<th>Key Issues</th>
<th>Solutions/Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive reduction in diesel sulfur</td>
<td>Remove sulfur from raw material of blend stream</td>
<td>- Low sulfur crude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Fractionation. Volume loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- HDS portion of blend streams. High cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Additional HDS for lower sulfur. High cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Incorporate high severity HDS. Higher cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Hydrocrack. Very high cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- GTL. Very high cost</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 Crude</th>
<th>PPM S</th>
<th>Vol Frac.</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>15</td>
<td>5500</td>
<td>15</td>
<td>2000</td>
<td>13</td>
<td>5300</td>
</tr>
<tr>
<td>FCC LCO</td>
<td>3</td>
<td>17500</td>
<td>3</td>
<td>6000</td>
<td>1</td>
<td>13000</td>
</tr>
<tr>
<td>Trt Dist.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trt Dist. (Severe)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>5000</td>
<td>33</td>
<td>1680</td>
<td>29</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</th>
<th>PPM S</th>
<th>Vol</th>
<th>PPM S</th>
<th>Vol</th>
<th>PPM S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>15</td>
<td>2000</td>
<td>0</td>
<td>2000</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>Distillate</td>
<td>7</td>
<td>5500</td>
<td>0</td>
<td>5500</td>
<td>0</td>
<td>5500</td>
</tr>
<tr>
<td>FCC LCO</td>
<td>0</td>
<td>17500</td>
<td>0</td>
<td>17500</td>
<td>0</td>
<td>17500</td>
</tr>
<tr>
<td>Trt Dist.</td>
<td>11</td>
<td>870</td>
<td>32</td>
<td>500</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Trt Dist. (Severe)</td>
<td>31</td>
<td>20</td>
<td>31</td>
<td>20</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>2360</td>
<td>32</td>
<td>500</td>
<td>31</td>
<td>20</td>
</tr>
</tbody>
</table>

Investment for Diesel HDS options

<table>
<thead>
<tr>
<th>Courtesy IFP</th>
<th>LSD</th>
<th>ULSD</th>
<th>ULSD &amp;cetane</th>
<th>ULSD 2stgPNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur, ppm</td>
<td>350</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Cetane No.</td>
<td>51</td>
<td>55</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>PNA, wt%</td>
<td>11</td>
<td>&lt; 3</td>
<td>&lt; 2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>ISBL capital</td>
<td>Base</td>
<td>1.65xbase</td>
<td>2.1xbase</td>
<td>2.7xbase</td>
</tr>
</tbody>
</table>
### Estimated Gasoline Sulfur Cost Reductions
*(Based on Reported Study Estimates)*

<table>
<thead>
<tr>
<th>Region</th>
<th>Sulfur Reduction PPM</th>
<th>Capital Cost $ Million</th>
<th>Barrels MBPD</th>
<th>$/MBPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>350-30</td>
<td>4,900</td>
<td>7,300</td>
<td>0.67</td>
</tr>
<tr>
<td>Canada</td>
<td>350-30</td>
<td>500</td>
<td>700</td>
<td>0.71</td>
</tr>
<tr>
<td>Europe</td>
<td>150-10</td>
<td>2100</td>
<td>3,300</td>
<td>0.64</td>
</tr>
<tr>
<td>Indonesia/Philippines</td>
<td>400-30</td>
<td>203</td>
<td>294</td>
<td>0.69</td>
</tr>
</tbody>
</table>

### Estimated Diesel Sulfur Cost Reductions
*(Based on Reported Study Estimates)*

<table>
<thead>
<tr>
<th>Region</th>
<th>Sulfur Reduction PPM</th>
<th>Capital Cost $ Million</th>
<th>Barrels MBPD</th>
<th>$/MBPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>340-15</td>
<td>5,300</td>
<td>2,600</td>
<td>2.04</td>
</tr>
<tr>
<td>Canada</td>
<td>500-15</td>
<td>1,000</td>
<td>400</td>
<td>2.50</td>
</tr>
<tr>
<td>Europe</td>
<td>350-10</td>
<td>4,600</td>
<td>3,000</td>
<td>1.53</td>
</tr>
<tr>
<td>Indonesia/Philippines</td>
<td>2000-1000</td>
<td>200</td>
<td>360</td>
<td>0.56</td>
</tr>
<tr>
<td>Indonesia/Philippines</td>
<td>500-150</td>
<td>460</td>
<td>360</td>
<td>1.28</td>
</tr>
</tbody>
</table>
Combustion Emissions

- Lead
- Hydrocarbons
- Carbon Monoxide
- Oxides of Nitrogen
- Carbon Dioxide
- Particulates
- Sulfur Dioxide/Sulfates
- Other toxic pollutants
- Water Vapor

Other Emissions

- Refueling Losses
displaced vapors

- Evaporative Emissions
diurnal, running losses, hot soak

- Crankcase Losses
due to "blow-by"

- Other Emissions
  - brake linings, tire wear, fluid leaks
Ozone Isopleth Plot (EKMA Diagram)

- Area of effective HC control
- 10:1 "Ridge"
- Constant Ozone Concentration
- Area of effective NOx control

Reactive Hydrocarbons (HCs)

Nitrogen Oxides (NOx)

Low O3

High O3

Less NO

Less HC

Sydney, Australia
25 October – 01 November 2003

Europe

Fuel Quality Strategies Training Workshop
Sydney, Australia
25 October – 01 November 2003
European Fuel Sulfur Levels (PPM)

- **Gasoline**
  - Euro 2: 600 PPM
  - Euro 3: 500 PPM
  - Euro 4: 50 PPM
  - Euro 5: 10 PPM

- **Diesel**
  - Euro 2: 500 PPM
  - Euro 3: 350 PPM
  - Euro 4: 50 PPM
  - Euro 5: 10 PPM

Widely Available:
- In 2005: 100%
- In 2009:

Emissions From Gasoline Cars In Europe

- **CO**
- **NOx**
- **HC+NOx**

% reduction from 1994 to 2010:

- **Euro I**
- **Euro II**
- **Euro III**
- **Euro IV**
Emissions From Diesel Cars In Europe

[Graph showing emissions reduction over time for Euro I to Euro IV standards.]

Penetration of Diesel Cars in Europe (% of New Sales)

[Graph showing penetration rates for different countries (Germany, Austria, Belgium, France, Italy, UK, Sweden) over the years 1997 to 2005. The graph includes a sales weighted average line.]
### Yearly Car Tax in Denmark

- 24 Different Car Classes Based On Kilometers Per Liter of Fuel
- Diesel Taxed More Than Gasoline
- Annual Increase with Inflation Plus 1.5% Per Year
European Agreement (g CO₂/km)

- Some 120 g/km Cars in 2000
- Target Range of 165-170 g/km in 2003
- Review Feasibility of 120 g/km for Average car by 2012 in 2003

Future Directions in Europe?

- Assure Filters or Traps Be Used Across the Board
  - EEV Standards with Tax Incentives
  - Tighter Standard(s)
- PM Standards – Current Standard Not Tight Enough
  - Ultra Fine PM
  - Toxic Emissions
- Diesel NOx Tightened To Gasoline NOx Standards
  - recent agreement on sulfur enables diesel NOx technology to accomplish this
- Maybe Even Tighter Gasoline Vehicle Standards
New Car Emissions Standards in the US

- HCs:
  - Pre-Control
  - 1975
  - 1981
  - 1987
  - 1993
  - 1999

- COs:
  - Pre-Control
  - 1975
  - 1981
  - 1987
  - 1993
  - 1999

- NOx:
  - Pre-Control
  - 1975
  - 1981
  - 1987
  - 1993
  - 1999

- PMs:
  - Pre-Control
  - 1975
  - 1981
  - 1987
  - 1993
  - 1999

Fuel Quality Strategies Training Workshop
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Module 2

US Tier 2 Standards

United States and California On-road Truck Engine Standards, Beginning with the 1988 Model Year
Key Motor Vehicle Regulations In California

- Catalytic Converters and Unleaded Fuel
- Required use of TWC and computer-based emission control
- On-Board Diagnostics II
- Low Emission Vehicle I + Phase I Gasoline
- Roadside Truck Inspections
- Phase II Gasoline
- Gasoline Trucks
- Diesel Trucks
- Low Emission Vehicle II
- On-Road Motorcycles
- Urban Transit Buses
- Diesel Trucks


California’s Goal: “Zero” Emissions

(g/mile)

1994 2004 2010

Phase 2 Phase 3 LEV I LEV II

HC NOx
California’s Family of Clean Cars

- **PZEVs**
  - Super Ultra Low Emissions
  - Zero Evaporative Emissions
  - 150,000 mile emissions durability
- **AT PZEVs**
  - Hybrid Electric Vehicles
  - Compressed Natural Gas Vehicles
  - Hydrogen Internal Combustion Engine Vehicles
- **ZEVs**
  - Battery Electric Vehicle
  - Fuel Cell Vehicles

---

### Engine Standards – 2Step Fuel Program

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25</td>
<td>Tier 1</td>
<td></td>
<td></td>
<td></td>
<td>PM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-100</td>
<td>existing Tier 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PM:100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100-175</td>
<td>existing Tier 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NOx: 50%</td>
<td>50%</td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>175-750</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PM: 100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;750</td>
<td>Tier 1</td>
<td>existing Tier 2</td>
<td></td>
<td></td>
<td>PM &amp; NOx: 50%</td>
<td>50%</td>
<td>50%</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standards requiring high-efficiency aftertreatment are shown **bold**.
For 50-70 hp engines, manufacturers may opt to preserve Tier 3 in 2008-2011 (no pull ahead), but PM trap requirement moves **bold** to 2012.
Diesel Particulate Filters

Trapped PM

Cell Plugs

Exhaust (PM, CO, HC)

Enter

Exhaust (CO₂, H₂O)

Out

Issues to balance:
- sulfate formation
- regeneration and back pressure
- Fuel Economy

Reductions:
- 80 to 95% PM
- 80-100% HC, CO
- > 80% toxins

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Comparison of Particle Emissions from SMPS.7: All Vehicles and Fuels - 50kph

A PM Solution Exists!

Electrical Mobility Diameter/nm

Fuel Quality Strategies Training Workshop
Sydney, Australia
25 October - 01 November 2003
PM and NOx Reduction System “DPNR”

Exhaust gas flow

Fine porous ceramic filter

NOx storage reduction catalyst coating

Exhaust gas

Fine porous ceramic filter

Toyota Motor Corp., July, 2000

PSA’s DPF System for Diesel Passenger Cars

Engine ECU

Software:
- Manager
- Regeneration strategy
- Diagnosis
- FORD

Fuel delivery

Fuel pump

Fuel tank

Additive tank

Dosing system ECU

Hydrocarbons

Common rail

Pressure loss sensor

Temperature sensor

CAT SIC DPF

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Estimated Cost of Controls
Light Duty Gasoline Cars

- Nothing: $0
- Engine Modifications: $150
- Oxidation Catalysts: $300
- TWC (1980’s Vintage): $500
- Tier 1: $600
- LEV/ULEV: $750
- LEV2: $857

Estimated Cost of Controls
Light Duty Diesels

- No Controls: $0
- Euro 1: $150
- Euro 2: $400
- Euro 3: $500
- Euro 4: $650
Estimated Cost of Controls
Heavy Duty Engines

<table>
<thead>
<tr>
<th>No Controls</th>
<th>Engine Mods</th>
<th>Euro 1</th>
<th>Euro 2</th>
<th>Euro 3</th>
<th>Euro 4</th>
<th>Euro 5</th>
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</thead>
<tbody>
<tr>
<td>$0</td>
<td>$250</td>
<td>$500</td>
<td>$2,500</td>
<td>$3,500</td>
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Estimated Cost of Controls
Motorcycles

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<th>Advanced Engine Mods</th>
<th>Catalysts</th>
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<td>$0</td>
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<td>$60</td>
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Benefits & Costs of Recent US EPA Motor Vehicle Pollution Control Regulation

Billions/Year

EPA Regulations

<table>
<thead>
<tr>
<th>Tier 2 Light Duty Vehicles</th>
<th>Low Sulfur Gasoline</th>
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<tbody>
<tr>
<td></td>
<td>2007-10 Heavy Duty Diesels</td>
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Asia

Fuel Quality Strategies Training Workshop
Sydney, Australia
25 October – 01 November 2003
### Gasoline Sulfur Levels in Bangkok 1998-2002

<table>
<thead>
<tr>
<th>Year</th>
<th>Average</th>
<th>% over 150 ppm</th>
<th>% over 50 ppm</th>
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<td>1998</td>
<td>197</td>
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<td>-</td>
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<tr>
<td>1999</td>
<td>175</td>
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<tr>
<td>2000</td>
<td>150</td>
<td>46.15</td>
<td>87.43</td>
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<td>2001</td>
<td>156</td>
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<td>2002</td>
<td>181</td>
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### Diesel Sulfur Levels 1998-2002

<table>
<thead>
<tr>
<th>Year</th>
<th>Average</th>
<th>% Above 360 ppm</th>
<th>% Above 50 ppm</th>
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<tbody>
<tr>
<td>1998</td>
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<tr>
<td>1999</td>
<td>367</td>
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<tr>
<td>2000</td>
<td>360</td>
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<td>2002</td>
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