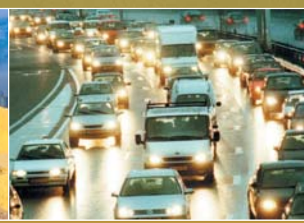
Fuels and Vehicles Working Group Report Series: Volume III



Fuel sulphur:

Strategies and options for enabling clean fuels and vehicles

IPIECA

International Petroleum Industry Environmental Conservation Association

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** This volume of the IPIECA Fuels and Vehicles Report Series is dedicated to the late Dr Neville Thompson (ExxonMobil and CONCAWE), in appreciation of his enthusiasm and support for the IPIECA Fuels and Vehicles Working Group and the Association's Fuels Network over many years.*

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Supplementary Documents

Additional information is provided in a series of short 'Supplementary Documents' which are included on the attached '*Fuel sulphur*' CD-ROM. These are referred to in the text where appropriate and are summarized below:

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Supplementary Document B: *Matching vehicle emission control technologies with fuel sulphur*

Supplementary Document C: *Crude oil characteristics and expected product yields*

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Introduction

Globally, personal mobility and goods transport is expected to grow rapidly commensurate with an expected increase of real per capita income. If current trends continue, while transportation-related emissions of air pollutants are expected to decline sharply in developed countries, substantial traffic growth is expected in developing countries. Maintaining and improving air quality in urban and urbanizing areas of many developing countries is therefore a key challenge.

Regional and national air quality management strategies should be based on analysis of the specific root causes of pollution, and understanding the contributions from all emissions sources, be they mobile, stationary, or residential and commercial. The key is to implement cost-effective strategies for controlling emissions from high-impact sources in a manner that will maximize public health benefits. Therefore, understanding the relative contribution of road transport to overall emissions is critical to assessing the potential impact of fuel and vehicle changes on air quality. This is a stepwise process.

Developing countries still using ***leaded gasoline*** are encouraged to place their highest priority on the development of a lead phase-out programme, as described in the IPIECA report entitled *Getting the lead out: downstream strategies and resources for phasing out leaded gasoline* [IPIECA, 2003] (available from the IPIECA website at www.ipieca.org or by clicking here). The primary air quality benefit comes from the fact that unleaded gasoline will be available globally in the near future, enabling the use of catalytic exhaust after-treatment systems. ***Low sulphur gasoline and diesel fuels*** will become the norm in the developed world after 2010 and will enable advanced emission control systems. That analysis concludes that if an appropriate 'road map' is devised now, the same could be true for many developing countries by 2030.

Unlike lead, sulphur is naturally present in crude oil, and must be removed in the refining process to create lower sulphur fuels. The removal processes present large technological and resource challenges. To assist developing countries in addressing these challenges the International Petroleum Industry Environmental Conservation Association (IPIECA) has developed this guidance document on fuel sulphur, which is the third in a series of reports prepared by IPIECA's Fuels and Vehicles Working Group. The series aims to provide decision makers with background and guidance on addressing fuels and vehicles issues in the context of an overall air quality management framework. This report considers the issues linked to the reduction of sulphur levels in transportation fuels, and discusses appropriate strategies and options to address these issues based on local circumstances.

IPIECA members recognize that:

- fuels and vehicles should be treated as an integrated system;
- both fuel sulphur and engine/vehicle condition contribute to emissions;
- costs are not just measured in terms of cents/litre but also in terms of the significant capital costs associated with needed refinery modifications;
- it is not always feasible, or appropriate, for countries to jump to the most stringent fuel and vehicles standards;
- the nature of air quality problems, as well as the primary contributors to those problems, may vary from country to country; and
- government/private resources are limited and should be directed at programmes that improve public health in order of public need and cost-effectiveness.

In moving forward, it is critical to recognize the significant economic implications of reducing the sulphur content of transportation fuels, and the differences, priorities and economic realities between the developed and the developing countries.

Six key principles for approaching the reduction of fuel sulphur

- Fuels and vehicles must be treated as an integrated system, where reductions in sulphur are linked to vehicle technologies in order to maximize emission reduction benefits.
- An understanding that both fuel sulphur AND engine/vehicle condition can contribute to emissions, leading in turn to the corresponding need to develop viable inspection and maintenance programmes in order to be able to draw long-term benefits from advanced vehicle technologies.
- A recognition of the trade-offs governments may face in relying on product imports, in some cases enabling them to take advantage of lower costs in the open market, versus potential security of supply, job and wealth creation benefits from relying on a local or domestic refinery.
- An understanding that costs are not just measured in terms of cents/litre but also in terms of the high capital cost associated with the relevant refinery modifications needed for lower sulphur fuels.

While IPIECA's members will continue to work on improving their refineries and distribution systems, in the normal course of their business they will continue to collaborate with stakeholders to address linked activities that could also lead to reduced emissions from transportation sources and air quality improvements. Such areas might include proper enforcement of emission limits and fuel standards, inspection and maintenance of vehicles, scrappage of older vehicles, and approaches to 'retrofit' vehicles with emission control devices. Using optimal approaches for reducing emissions from both 'new' and 'in-use' vehicles will ensure that full benefits are obtained from reduced sulphur levels in transportation fuels.

Many factors determine the specific nature of local and regional air quality issue(s). Identifying and analysing specific root causes for air quality problems will point towards the most effective control strategies. All sources of air pollution, whether mobile, stationary, or residential and commercial, should be investigated as part of a comprehensive strategy. The most important consideration should be to link cost-effective control of emission sources that also provide significant public health benefits. Some such source categories might include: space heating, indoor cooking, transportation and waste incineration. Further guidance on this matter may be obtained from, among others, the IPIECA report entitled *Clearing the air: Strategies and options for urban air quality management* [IPIECA, 2004] (available from the IPIECA website at www.ipieca.org or by clicking here).

- A recognition that it is not always feasible, or appropriate, for countries to jump to the most stringent fuel/vehicles standards, especially if the infrastructure and government regulatory authorities are not in a position to implement and enforce regulations surrounding the supply of these new fuels and vehicles.
- Accepting that the nature of air quality problems, as well as the primary contributors to those problems, may vary from country to country, and respecting that limited government/private resources are available, hence resources should be directed at programmes to improve public health in order of cost-effectiveness and public need.

IPIECA and its member companies and associations stand ready to provide technical assistance to developing country governments in making a transition to lower sulphur fuels.

Understanding the contribution of road transport relative to other emission sources is critical to assessing the overall impact of fuel and vehicle changes on emissions inventories and air quality, and issues other than sulphur, for example lead phase out, may be a higher priority for developing countries. For guidance on lead phase out, interested parties may refer, amongst other sources, to the IPIECA report entitled *Getting the lead out: downstream strategies and resources for phasing out leaded gasoline* [IPIECA, 2003] (available from the IPIECA website or by clicking here).

Lower sulphur fuels have been shown to be important to enhance the performance of catalytic emission control systems; very high levels of sulphur can reduce the activity of the catalysts. Unlike lead, sulphur is naturally present in crude oil, and must be specifically removed in the refining process to create lower sulphur fuels. The guidance provided in this document focuses on technical considerations for successful introduction of lower emission vehicles and the reduction of the sulphur content of fuels to allow advanced automotive control technologies to meet current standards. In addition, information is provided on the role of retrofits and inspection and maintenance programmes. It also discusses refining strategies for phasing down sulphur and addresses the need for concurrent infrastructure improvements to facilitate the delivery of high quality fuels to the markets.

IPIECA fully appreciates that refineries in many developing countries will face real challenges over the multi-million dollar investments required to move to lower sulphur fuels. IPIECA members support an approach to sulphur reduction based on the six key principles shown in the box on pages 6–7. Due to the significant economic implications of phasing down fuel sulphur, it is critical that all stakeholders recognize the differences between the situation in the United States (USA) and the European Union (EU), where private ownership of refineries is the norm, and the situation in developing countries where governments are, in most cases, owners of, or majority partners in, the fuel refining and marketing infrastructure.

Key policy considerations

The key factors decision makers ought to consider when developing strategies to reduce sulphur in fuels and lower vehicle emissions include:

- emission control technologies and age of the existing fleet;
- current fuel sulphur levels, and expected phase-in of new vehicle emission standards;
- vehicle usage characteristics, and vehicle maintenance and repair capabilities; and
- the capabilities of the refining, distribution and retail infrastructure.

The strategic implications of any proposed fuel policies require certain issues to be considered, such as: security of fuels supply, economic competitiveness, opening new markets, and employment. To maximize the chances of successful implementation, all stakeholders should be consulted including state and local administrators, refiners and fuels distributors, vehicle manufacturers and importers, along with public representatives and community groups. Figure 1 shows the linkages between the various categories of issues and analyses that are needed when developing a detailed local implementation strategy. These issues will be discussed further below and they can be used as a framework for developing an integrated strategy for phasing down fuel sulphur.

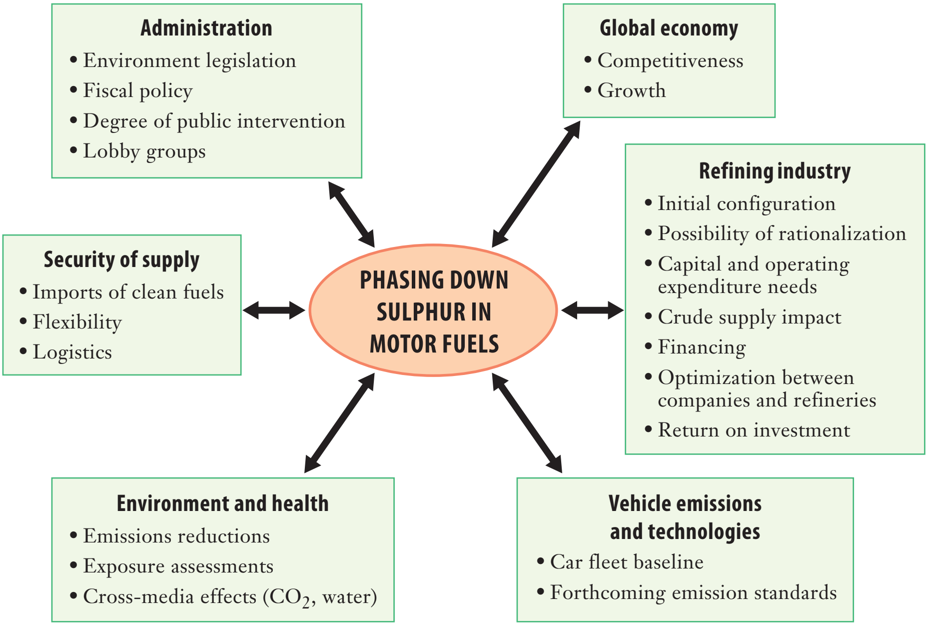
Strategies to reduce emissions from the transportation sector in a given country should be based on factors pertinent to that country and/or region. Countries may have domestic refineries, and those refineries will differ in their complexity and flexibility to produce cleaner fuels. In developing their strategies countries should consider the range of options and devise a country specific 'road map', for example:

- In the **short-term**, countries could switch to 'sweet' (low sulphur) crude, which could be more expensive to import but less expensive to process, and/or they could import lower sulphur finished products for use in areas where the air quality is particularly bad; while
- More **long-term** alternatives might include regional harmonization of fuels and vehicles standards concurrent with upgrading refineries' processing capabilities to produce lower sulphur fuels.

Since the cost of reducing sulphur in motor fuels and its impact on urban air quality will vary from country to country, decision makers will have to consider whether their best way forward is to phase down sulphur over time, or to 'leapfrog' to ultra-low* sulphur fuels immediately. Moreover, whatever policy options are considered it is imperative that automotive fuels and vehicles be treated as an integrated system. Advanced vehicle control technology needs reduced sulphur levels to maximize emission reduction benefits.

In the USA, EU and Japan, changes to fuel properties have been introduced over time in line with reductions in vehicle emission limits requiring new vehicle technology. Developing countries that are now facing emerging air quality management issues may benefit from this accumulated experience. This will help to develop implementation strategies that are matched to the severity of their air pollution problem, fuel refining, distribution and supply infrastructure, and their priorities for allocation of resources.

Figure 1: Schematic representation of interlinkages to be considered when planning to phase down sulphur in motor fuels



* The definition of ultra-low sulphur is different in the USA and Europe (see Glossary).

The importance of integrated air quality management

An integrated and structured air quality management approach is needed to establish and attain air quality objectives at the national and local levels. As discussed in many guidance documents, including IPIECA's *Clearing the air: Strategies and options for urban air quality management* [IPIECA, 2004] (available from the IPIECA website or by clicking here), an integrated approach requires appropriate technical information, for example: emission inventories; ambient air quality monitoring; air quality prediction models; and assessment of gaps between the measured and desired air quality. Such a programme, in addition to sound technical information, should also be based on cost-effectiveness analysis, transparency of decision making and stakeholders' involvement.

The impact of road transport on air quality

Road transportation impacts air quality via multiple processes, including:

- exhaust emissions from vehicles and other combustion sources;
- evaporation of fuel hydrocarbons from vapour and liquid fuel lines and storage tanks onboard motor vehicles; and
- emissions of non-fuel-related species (e.g. tyre and brake wear, particulate matter).

These emitted compounds react in the atmosphere to form ozone, secondary particles and other secondary pollutants. Combustion also produces greenhouse gases such as carbon dioxide.

Transport is only one of the contributors to the overall emissions inventories that influence air quality in a given area. Table 1 lists the published data documenting the share of emissions attributable to transport for various cities around the world. Although the data is only a small sample, it demonstrates the variability amongst regions and cities of the transport sector contribution to total emissions inventories. As noted in '*Clearing the air*' the effectiveness of transport-oriented measures to improve air quality will vary according to local conditions and accurate understanding of all sources.

Table 1: Percentage of emissions due to vehicles in selected cities

City/region	carbon monoxide	volatile organic compounds	oxides of nitrogen	sulphur dioxide	particles
Beijing	39	75	46	n.a.	not available
Budapest	81	75	57	12	not available
Cochin	70	95	77	n.a.	not available
Colombo	100	100	82	94	88
New Delhi	90	85	59	13	37
Lagos	91	20	62	27	69
Mexico City	100	54	70	27	4
Santiago	92	81	82	25	10
São Paulo	97	89	96	86	42

Based on the United Nations Global Inventory of Transport Emissions (GITE, 2002).
Sources: Dietrich Schwela and Olivier Zali, Eds. 'Motor vehicles and air pollution,' in *Urban Traffic Pollutio*n (London, E & FN Spon, 1999); Bekir Onursal and Surhid P. Gautam, *Vehicular Air Pollution: Experiences from Seven Latin American Urban Centers*, World Bank Technical Paper 373 (Washington, D.C., World Bank, 1997); and Christopher Zegras and others, *Modeling Urban Transportation Emissions and Energy Use: Lessons for the Developing World* (Washington, D.C., International Institute for Energy Conservation, 1995).

The linkage between air quality and health

Outdoor air pollution can originate from point sources, which may affect only a relatively defined area, or from many small and diffuse sources. In any given area, a variety of diffuse sources, such as traffic, area sources (for example, wood burning, paint drying, residential heating) and point sources (for example, industrial boilers, power plants) emit a mixture of compounds to the atmosphere. In addition to those pollutants emitted directly by local sources, some pollutants are created by a chain of complicated atmospheric reactions or are transported over medium and long distances.

The relative contribution of emission sources to human exposure to air pollution varies according to regional conditions and lifestyle factors. For some pollutants, indoor sources may be of greater importance than outdoor sources in terms of exposure, but this does not diminish the importance of outdoor pollution. Pollutants produced outdoors may penetrate into the indoor environment and may affect human health from both indoor and outdoor exposure.

Excessively high levels of air pollution are recognized as having an impact on human health; however, the path from transportation emissions to human health is anything but straightforward. Therefore, the World Health Organization (WHO) has developed recommended ambient Air Quality Guidelines, or targets, as indicators for population exposure. Countries that want to use this method to improve air quality can use these targets and air quality monitoring guidelines to document ambient conditions (see www.who.int). The WHO guidelines provide specific air quality targets for SO_2, CO, NO_2, O_3 along with guidance concerning the control of airborne particles with diameter < 10 µm (PM_{10}) or < 2.5 µm ($PM_{2.5}$).

Current strategies for improving air quality are focused worldwide on the target compounds identified by the WHO, with special attention being given recently to the contribution of diesel exhaust to the overall atmospheric loading of airborne particles. Diesel exhaust is a complex mixture of hundreds of constituents in either gas, liquid or particle form. The gaseous phase of diesel exhaust contains numerous low-molecular-weight hydrocarbons. Diesel exhaust also contains fine particulate matter (diameter < 2.5 µm), and also includes a subgroup of ultra-fine particles (diameter < 0.1 µm), which are believed to be liquid droplets.

Extensive ongoing research is attempting to better characterize the health effects that could be attributable to exposure to diesel exhaust and other particulate matter. The investigations range from studies of primarily chronic non-cancer respiratory effects all the way to the potential for developing lung cancer. A good summary of current understanding of the health impacts of diesel particles has been issued by the Health Effects Institute (HEI), which also includes a brief description of additional studies that are being undertaken to further elucidate these linkages [HEI, 2003].

The role of 'fuel-vehicle' strategies for air quality improvements

The magnitude of the air quality problem and the contribution of the transport sector to overall emissions will determine the extent of motor vehicle emissions control requirements. The biggest component of a vehicle emission control strategy in any air quality management plan must be improved vehicle technology, which can be enabled, or assisted, by changes to fuel quality.

While fuel characteristics are important, their emissions effects alone are relatively small:

- Fuel changes alone usually give limited emissions reductions from the existing vehicle fleet.
- Fuel changes by themselves will not generate the magnitude of emissions reductions achievable through the phase in of new lower emitting vehicles.
- Fuels may need to change to enable vehicle technologies, especially those used in lower emitting vehicles.
- An appropriate level of fuel sulphur is important for various catalyst and/or particulate trap-equipped vehicles.

A cost-effective air quality management system requires local and national authorities to simultaneously address fuel quality, vehicle technology, vehicle maintenance and road/traffic conditions. See Supplementary Document A: *Diesel emissions reduction in Asian cities* which includes a case study of a hypothetical Asian city showing the emission reductions that can be achieved by changing vehicle technology, reducing fuel sulphur and implementing an inspection and maintenance (I&M) policy.

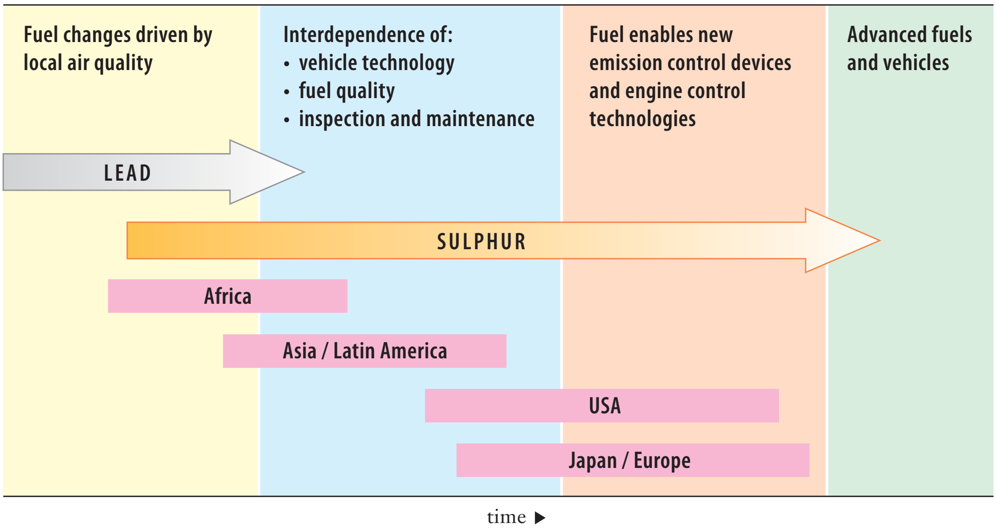
Figure 2 presents the evolving stages of the 'Fuel-Vehicle System' concept as the different regions have adopted future fuels and vehicles measures. The key initial driver was almost always the removal of lead from gasoline to allow introduction of catalyst-equipped vehicles and reduce airborne lead levels.

This is usually followed by a period when fuel, vehicle technology and I&M are interdependent and change in parallel to reduce emissions to very low levels, with the key fuel property being sulphur—the subject of this report. The final stage would be radical new technologies such as fuel cell vehicles, which are still a long way from implementation and whose future is uncertain.

The USA and Europe have lowered sulphur levels in a stepwise approach, over many years, while aligning fuel quality to vehicle technology requirements. The introduction and subsequent improvement of catalytic controls on vehicles to meet tighter tailpipe standards led to significant emission reductions with fuel sulphur limits of 500 ppm in the EU and 1000 ppm in the USA. Further discussion of these sulphur limits and the vehicle technologies they support is provided in the next section titled 'The role of fuel sulphur: vehicle emissions control considerations'.

This trend of linking changes in fuel parameters to vehicle technology requirements—as needed to attain tighter emission standards—is spreading to more

Figure 2: Evolving stages of clean fuel and vehicle technology



regions and countries over time. Tables 2 and 3 provide an historical evolution of exhaust emission and gasoline and diesel fuel sulphur limits in Europe and the USA. Developing countries may be able to learn from experience gained by other countries and develop their own 'road map' for both vehicle emission standards and corresponding fuel quality requirements, which should include an evaluation of the implication of intermediate steps.

Some countries might be ready to jump immediately to the most advanced technologies. However, for the vast majority of countries, a 'quantum leap' to ultra-low sulphur fuels alone would not be in their best economic or environmental interests, as the benefits would be small if they cannot concurrently introduce the corresponding high technology vehicles. The types of vehicles in the country, or local area, should guide the level of fuel sulphur needed at any particular phase of the 'road map'.

Table 2: Gasoline sulphur limits and vehicle emission standards in the USA and Europe

USA			Europe		
Year	**Emission limitation**	**Max. fuel sulphur (ppm)**	**Year**	**Emission limitation**	**Max. fuel sulphur (ppm)**
1975	First catalyst (oxidation)	1000	Pre-1993	Country specs (leaded)	1000–2000
1980	Tier 0 (3-way catalysts)	1000	1993	Euro 1 (3-way catalysts)	1000
1994	Tier 1	1000	1996	Euro 2	500
1999	NLEV	1000	2000	Euro 3	150
2004	Tier 2(*)	80(30)	2005	Euro 4	50(10)

(*) The Tier 2 standard calls for an average of 30 ppm and a per gallon cap of 80 ppm. This results in a much lower sulphur level than a simple cap at 80 ppm. Some of the gasoline marketed has to be below 30 ppm by this definition.

Table 3: Diesel sulphur limits and vehicle emission standards in the USA and Europe

US heavy duty			Europe light duty		
Year	**Vehicle control**	**Fuel sulphur (ppm)**	**Year**	**Standard**	**Fuel sulphur (ppm)**
			1980	EEC/75/716	5000
1988	Engine mod	5000	1989	EEC/87/219	3000
1993	Engine mod	500	1993	Euro 1	2000
1998	Engine mod	500	1996	Euro 2	500
2004/2006	EGR	500/15	2000	Euro 3	350
2006/2010	After-treatment	15	2005	Euro 4	50(10)

The role of fuel sulphur: vehicle emissions control considerations

General

The main contributor to lower vehicle emissions over the past 30 years has been the introduction of vehicles with exhaust catalysts. Certain fuel properties are important to enable these catalysts to operate effectively over the life of the vehicle. The first worldwide priority has been, and still is, the phase out of lead, a catalyst poison, to enable effective after-treatment on gasoline vehicles.

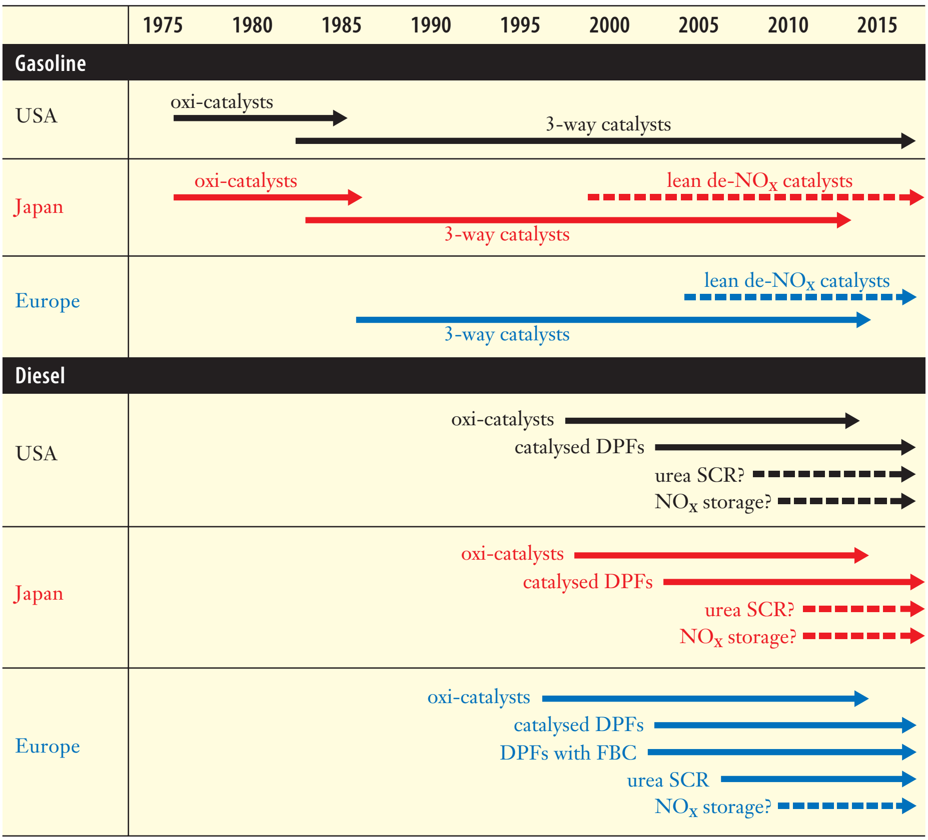
Unlike lead, which is added to gasoline during the refining process, sulphur is a naturally occurring element in crude oil. Although the level of sulphur in the fuel can also affect the performance of vehicles' catalysts, it does so to a much lesser extent as compared to lead, which is a severe and irreversible catalyst poison. Fuel sulphur levels should be set to match the corresponding vehicle emissions control technology in each regional market.

Vehicle emissions control technologies

Clearly, improved vehicle emission control technology can lead to substantial reductions in emissions. In areas where vehicle emission controls have not been applied, the adoption of either the US or the European emissions standards that were in effect for new vehicles during the mid to late 1990s will provide a significant long-term reduction in emissions from the on-road motor vehicle fleet. These standards can be adopted while maintaining gasoline and diesel sulphur levels in the 300–1000 ppm range as discussed below. The imposition of the most advanced US or European emissions standards for new vehicles will provide a much smaller incremental benefit that may not be cost-effective.

Figure 3 depicts the sequence of introduction of automotive technologies in the USA, Europe and Japan for both gasoline and diesel fuelled vehicles. The timeline shown

Figure 3: Timeline depicting past, present and anticipated future introduction of emission control technologies



extends from 1975, when the first catalytic converters were introduced, to 2015 when technologies that are currently in the development stage are expected to become more routinely available. Supplementary Document B gives a more complete description of the different vehicle emission control technologies and their sensitivity to sulphur.

Diesel retrofits

Diesel engines can, in some cases, be retrofitted with various types of exhaust after-treatment systems, to reduce emissions. Oxidation catalysts can be used on many older light- and heavy-duty engines, to give a significant (~25%) reduction in PM emissions and also reduce HC and CO.

Some types of particulate traps can also be retrofitted: in particular, the continuously regenerating trap (CRT) and the catalysed diesel particulate filter (C-DPF) can give substantial (~90%) reductions in PM emissions with 50-mg/kg-sulphur fuel [DECSE, 2001]. However, these systems are most effective only when the engine exhaust temperature is high enough to regenerate the traps, otherwise the filters can fill with soot and clog, sometimes rapidly. They are not suited to older, heavily polluting vehicles, and need to be tailored to individual vehicles and require good maintenance practices. They can also show an increase in fuel consumption, so are regarded by some as not the most cost-effective solution. The approach is generally more suitable to heavy-duty vehicles, city buses or taxi fleets, rather than private cars. Flow-Through Filters (FTFs), which use wire-mesh or 'tortuous flow' designs to help oxidize most particles, are currently being developed and may be useful for older heavy-duty diesel vehicles, especially those with mechanical controls. There is a social benefit and public perception value from lowering black smoke levels. Many successful retrofit campaigns have been reported in US cities such as New York, Los Angeles, Seattle and more, along with similar projects in Europe and Japan. Pilot studies conducted under typical 'local-use' conditions are important for the effective application of retrofit strategies, and they are now starting in Latin American and Asian countries.

The role of inspection and maintenance

There is no doubt that the biggest reductions in vehicle emissions come from the introduction of new engine technology and after-treatment systems, especially the use of catalysts on both gasoline and diesel vehicles. Performance of this technology can be enhanced by fuel sulphur reduction, as discussed above. However, the benefits of these technologies are sustained only as long as the emission control technology devices are operating correctly. If a gasoline catalyst is rendered ineffective, by misfuelling with leaded gasoline, or by removal, emissions could rise by a factor of 10, and may be higher than for a non-catalyst vehicle. There is a common misconception that vehicles fitted with emission controls do not perform as well as vehicles without them, thus encouraging 'tampering' with control systems. This perception is false and public education programmes need to make consumers aware of the benefits of emissions control devices, as well as the need to maintain them properly and ensure their durability.

Thus it is essential to have a system of inspection and maintenance (I&M) to check and control emissions from vehicles in service and ensure that they continue to operate as designed. This is important even if catalysts are not installed, because poor engine tuning can also substantially increase emissions. Clearly this becomes even more important as advanced emissions control technologies are added to vehicles, and with the introduction of advanced technology engines into countries' fleets. The subject is well reviewed in a recent World Bank Report [World Bank, 2004] which discusses the issues involved.

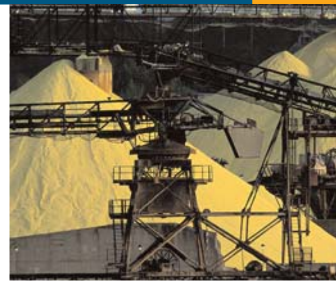
A robust I&M system should be based on test protocols that are designed to:

- **minimize** false passes or false failures;
- make it **difficult** to cheat or avoid inspection;
- **minimize** measurement differences among test centres; and
- **maximize** precision and accuracy.

Experience in Mexico City and elsewhere has shown that large centralized test-only centres work better than decentralized test-and-repair garages that are more open to fraud. If vehicles are equipped with on-board diagnostic systems (OBD), the test-only centers could also integrate OBD readings into the overall I&M procedure. In addition education campaigns should be undertaken to improve maintenance procedures, especially of small two-stroke engines.

Whatever system of I&M is chosen, the government must be willing and able to provide the substantial resources to audit and supervise the programme, even if the supervision is provided by a third party. This is a mandatory element for such schemes in order to guarantee their objectivity and transparency. In addition to adequate oversight of the I&M programme, governments also must be willing to provide funding to ensure that: (a) diagnostic and repair equipment is available in sufficient quantities; and (b) mechanics have adequate training to perform vehicle maintenance and repair efficiently.

A discussion of various approaches to detecting and repairing malfunctioning vehicles is included in Supplementary Document B: *Matching vehicle emission control technologies with fuel sulphur*. As newer technology vehicles are introduced into the fleet it is important to ensure that the small percentage of 'high emitters' do not negate the progress achieved by new technology introduction.



Lower sulphur fuels: refining and logistics basics

Crude oil, or petroleum, is a complex mixture of thousands of different molecules of varying sizes, their size being determined by the number of carbon and hydrogen atoms joined together. The wide range of size and configuration of crude oil molecules means that their boiling points range from ambient temperature to higher than 800 °C. Supplementary Document C contains further information about chemical composition, typical distillation yields and characteristics of a range of crude oils from different regions of the world.

Refineries must convert crude oil into the products that customers need using many different processes, which are briefly described in Supplementary Document D, while meeting local or international specifications including sulphur content. Global petroleum refining operations are undergoing many changes; equipment design has advanced greatly, product demand has shifted, specifications have become more stringent and feedstock has changed with varying sources of supply.

A number of technologies are available to reduce fuel sulphur content, which are also described in Supplementary Document D. The main issues are the availability of substantial capital to finance refinery upgrades and local capability to undertake the needed design and construction. All the technical considerations discussed in the Supplementary Documents must be put into the local context via detailed implementation strategies that should consider:

- sources of crude oil that are available to local refineries, and the security of their long-term supply;
- capital requirements to modify and upgrade local refineries, based on their current configuration; and
- improvements needed to local and/or regional infrastructure to transport low sulphur products to the market while avoiding contamination and/or adulteration.

Strategies and policy options

When national and regional authorities want to evaluate the relevance of phasing down automotive fuel sulphur in the framework of their overall air quality management programme, they have several routes open for implementation. The steps to be followed have been discussed above and also described in many guidance documents [World Bank, 2004; IPIECA, 2004; and others]. These guidelines, together with their knowledge of current local conditions, will assist them in determining the most appropriate way forward. Experience in dealing with air quality management issues in many parts of the world over the past 30 years has demonstrated that there is no easy route to achieving emission reductions and improved air quality; doing so requires an integrated effort, and a range of measures and strategies that, when taken together, will lead to the attainment of desired air quality goals.

For an illustrative checklist of items to be addressed when considering options for phasing down sulphur in automotive fuels see Supplementary Document F: *Topics to be addressed when evaluating options for reducing fuel sulphur*. It is expected that the degree of emissions control required will vary from country to country and from location to location. Using such a systematic approach, as discussed below, will focus the decision-making process and will maximize benefits.

Strategies for reducing vehicle emissions

Strategies can rely on measures that are either technology-oriented, targeting the vehicles and fuels used, and maintenance practices within the sector, or behavioural, seeking to reduce (or prevent increases in) the amount of activity of the most polluting vehicles. Such measures may also focus on systemic aspects of the transport system, i.e. the ways in which the transport network influences either the aggregate amount of vehicle use or the emissions intensity of individual vehicles.

Important factors that can impact the effectiveness of any mobile source control strategy ought to be considered, including the:

- relative contribution of mobile sources to local air pollution;
- make-up of the current and future vehicle fleet and expectations for future growth;
- length of time needed to introduce new low emission vehicles; and
- rate at which older vehicles leave the on-road fleet.

***Local practices regarding vehicle maintenance and compliance with regulations influence greatly the benefits that can be realized from vehicle emission control strategies*.**

Careful consideration needs to be given to local conditions, for example: the level of vehicle use; the age of the vehicle fleet and the technology it utilizes; the extent to which vehicles are properly maintained; and the availability of appropriate fuels and the extent to which they are used properly. The factors that need to be considered in these four areas are elaborated briefly in Supplementary Document G: *The vehicle-fuel system: factors for consideration by policy makers*. A more complete discussion of these issues can be found in a recently published World Bank document [World Bank, 2004].

When discussing the impact of new technologies it is important to quantify the benefits in absolute terms, rather than percentages: in other words, it is important to state the starting baseline. See Supplementary Document H: *The importance of considering the starting baseline* to view an illustrative example of this issue.

A comprehensive strategy to reduce the emissions of motor vehicles will need to address practical implementation issues and be tailored to the resource limitations, technological effectiveness and social feasibility of success. When evaluating fuel sulphur strategies it is also important to consider the local and regional fuel production and distribution infrastructure. Fuel specifications that have been developed in one region may not be cost-effective, or may require a long lead-time, when applied in a different region. The possibility of local, regional, national or multinational fuel specifications must be considered for each individual situation, based on specific market, financial and political considerations

The vehicle-fuel system

Control of vehicle emissions and fuel sulphur levels should be carried out as part of a coordinated plan to address all local sources of air pollution, including stationary sources along with mobile sources. The plan should be specifically tailored for the city, country and region of interest.

When evaluating policy options it is imperative that automotive fuels and vehicles be treated as an integrated system; in particular, reductions in sulphur need to be linked to the introduction of advanced vehicle technologies in order to ensure significant emission reduction benefits. Thus any policy should include parallel regulation in the three key areas of:

- vehicle emission controls;
- fuel quality; and
- inspection and maintenance (I&M).

Although changing fuel quality alone is generally not cost-effective, within the vehicle-fuel system, the two key fuels-related issues to be considered include:

(a) specifications, notably **sulphur content**, for clean fuels and, more generally, gasoline and diesel **quality standards**; and

(b) distribution, logistics and the potential for **adulteration** of fuels.

In the developing world, in addition to examining North American, European or Japanese strategies for cars and trucks, it is of particular importance to consider the emissions contribution of motorcycles and three-wheelers equipped with two-stroke engines. The design limitations that are inherent in these vehicles lead to extremely high emissions, especially smoke and unburned hydrocarbons from use of excess lubricant. The low octane requirement of these engines also makes fuel adulteration very easy. In this regard, the governments of Taiwan and Thailand have elected to ban such two-stroke engines. Clearly, any programme to eliminate two-stroke engines, should also include setting standards for new motorcycles and three-wheelers and should allow a reasonable time frame for fleet turnover. Although such measures are difficult to undertake, and often unpopular because of the need for mobility and the low cost of two-stroke motorcycles, they are essential. In some areas such measures might prove to be the most effective means, within a comprehensive air quality management programme, to reverse the degradation of urban air quality.

Framework for resource prioritization

Once the required level of emissions reductions has been established, then the appropriate government agency should evaluate the different possible routes to achieve these reductions, and the associated costs for each route. While the discussion below focuses on the costs and benefits of changing vehicle technology and reducing sulphur from motor fuels, these should be compared against the costs and benefits achievable from controlling emissions from other (e.g. stationary) sources.

The analysis must take economic and social factors into account, including:

1. availability of capital;
2. infrastructure changes that may be required;

3. availability of human and technical resources to implement the changes;
4. availability of human and technical resources needed to maintain the changes; and
5. future control programmes that might result in stranded investments.

While all elements listed are very important for a complete analysis, item 4 above is of particular importance. For control programmes to be effective adequate enforcement mechanisms and technical capabilities must be in place. For example, new vehicles will only provide low emissions if the appropriate emission standards are in place and all new vehicles comply with them. Equally, the benefits will be lost if the vehicles are not properly maintained, or if incorrect fuels (e.g. leaded gasoline) are used.

When prioritizing resources it should be recognized that although lowering sulphur may slightly reduce emissions from existing technologies the full benefit is derived from the prerequisite to reduce sulphur levels so that the newer emission control systems are able to operate effectively. Setting fuel sulphur levels too high may initially save money on refinery investments but result in higher vehicle emissions and thus waste resources invested in vehicle control systems. Conversely, setting fuel sulphur levels too low may not result in significantly reduced emissions and could waste capital invested in refinery modifications, if corresponding low emission vehicles, equipped with the appropriate technology are not available in the local area.

Developing refining and supply strategies

With the current trends for tighter specifications for both gasoline and diesel, it is important that a long-term strategy exists for meeting these goals. Many strategy documents have been developed in countries and regions around the world and the summary below does not intend to be all-inclusive, merely to outline some options for developing such strategies. Depending on the specific local conditions the solutions will probably be unique [see for example ASEAN, 2002].

In addition to refinery modifications it will be necessary to upgrade off-site facilities to enable handling of these higher specification products. When conducting a complete evaluation it will be important to maximize return on investment by taking into account the potential for cost-effective refinery revamps, energy savings and opening up new markets as part of an overall financial analysis.

Options analysis

A clean fuels strategy should be developed in the same way as any other investment decision-making process. Typically the steps involved in such strategy development are:

1. Define the objectives.
2. Develop a wide range of ideas for possible solutions to meet the objectives, which could include holding brainstorming sessions with refinery, licensors and contractors personnel.
3. Develop selected options for further consideration.
4. Cost the options and assess the economic viability.
5. Recommend a strategy and agree a way forward, which may include an investment 'road-map'.

See Supplementary Document I: *Present and future investment in the refining business in Latin America and the Caribbean* for a case study on this topic.

Refinery objectives are, typically, to produce clean fuels meeting specifications at the lowest possible cost and, at the same time, give the best return on investment (see Box 1). It is important to recognize that there are trade-offs for each of the options contemplated and they will need to be developed by taking into account the different aspects pertinent to the particular refinery. Recommended steps for the overall options analysis include:

- reviewing the options for **product import** and/or export;
- considering **crude substitution**, i.e. changing the ratio of sweet to sour crude processed;
- increasing **investment in off-site facilities** rather than new process units to maximize the use of existing facilities and allow greater blending and logistics flexibility; and
- avoiding unnecessary investment in upgrading facilities by taking advantage of **refinery investment synergies** and using **product or component swapping** with neighbouring refineries.

Additional planning considerations

Many different approaches can be considered when developing a specific 'road-map' to lower sulphur fuels. As indicated above they will include assessing the crude supply and refinery processing needs all the way to product marketing and logistics. Table 4

Box 1: Possible refinery modification steps for reducing diesel sulphur

The steps below and the accompanying figure attempt to encapsulate lessons learnt for staging refinery investments when phasing in lower sulphur fuels. These stages are particularly applicable to simple refineries with no, or minimal, existing hydrotreatment capacity.

1. **Switch to low sulphur crude:** this will not attain 500 ppm sulphur, but it could get sulphur levels down to around 1000 to 2000 ppm.
2. **Install a small hydrotreater:** this can be sized to treat ~50% of refinery output. Combining this with a switch to lower sulphur crude could be a useful strategy. Higher sulphur straight-run (~1000 ppm sulphur) can be blended with the fraction that has been hydrotreated, thus producing a final product with about 350 to 500 ppm sulphur.
   - *Note: when a future decision is taken to move to a lower sulphur specification, the refinery can then build a second hydrotreater to operate in parallel. This stages the capital investment and provides redundancy with one hydrotreater available while the other is down for maintenance.*
3. **Install a large high-pressure hydrotreater:** this would include a single-stage high-pressure processing unit that could make 50 ppm or lower sulphur products, depending on the severity with which it is operated. If financing is available for such a high-pressure unit it could be built and run initially at lower severity to make 500 ppm sulphur products, which reduce initial operating costs until lower sulphur fuels are required.
   - *Note: for equivalent-size units lower operating costs are associated with lower hydrogen consumption and longer catalyst cycle time (4–5 years instead of ~2 years for 50 ppm sulphur).*
4. **Install a hydrocracker**—this is the most expensive option (probably four to five times more than a high-pressure hydrotreater). This would be justified when an increase in diesel/kerosene yield is needed.

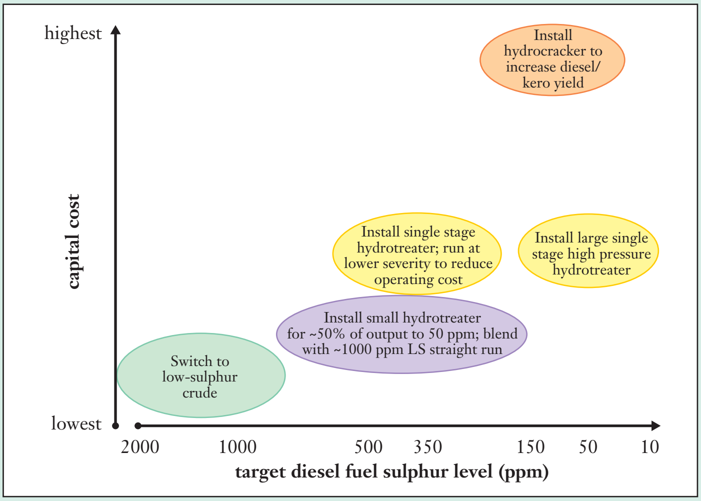


Table 4: Listing of potential studies needed for developing a refining 'road-map' to lower fuel sulphur levels

Study area	Brief description
Refinery planning	Economic studies to evaluate the processing options for a given refinery. These studies can cover potential changes to feedstock qualities and product specifications and assess the potential impact of changes to process units (via revamp or addition) and product blending options.
Revamp options	Innovative design studies directed at making the most effective use of existing process plant to meet new product specifications and to maximize throughput.
Hydrogen management	Studies to determine the optimum use of hydrogen within the refinery covering production, recovery and purification options, and import and export opportunities.
Energy efficiency	Studies aimed at improving energy efficiency within a process unit or complex.
Technology evaluation	Independent evaluation studies to compare available technologies (licensed or not) for a particular application.

provides a listing of recommended technical studies that are required to examine these issues.

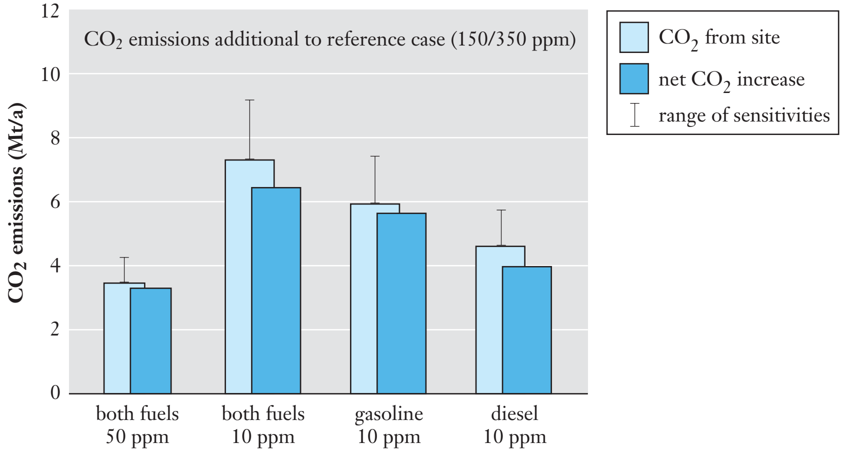
Additional impacts of fuel sulphur reductions

Reducing sulphur content has a significant impact on a number of other fuel properties, some of which have safety implications and must be taken into account. These items, to be further considered include:

- **Energy use**. The energy that is needed for the additional processing and to produce the hydrogen used to remove the sulphur will result in extra emissions of carbon dioxide. Figure 4 presents the correlation between additional carbon dioxide emissions and various sulphur levels in motor fuels, based on the assessment of EU refineries with a starting point of 150/350 ppm sulphur in gasoline/diesel respectively [CONCAWE, 2005]. It should be noted that while this represents the general trend, the size of the effect would depend on existing and new refinery technologies.
- **Octane loss**. Hydrotreatment can, in addition to removing sulphur, saturate some of the olefinic hydrocarbon components of the fuel. In the case of gasoline,

Figure 4: Reducing sulphur increases greenhouse gas emissions from refineries

Source: CONCAWE report No. 8/05 [CONCAWE, 2005]



this can result in octane loss, which needs to be replaced, an inefficiency of the process that increases its cost in addition to extra energy consumption. Developments in catalysts and reactor technology are improving the efficiency with which sulphur can be targeted, thus minimizing these octane losses. See Supplementary Document D: *Refining, sulphur removal and distribution basics* for more information on octane loss.

- **Lubricity.** In contrast, the hydrotreating process when applied to diesel streams tends to increase cetane number with beneficial effects. However it will also remove some of the active polar species that provide lubricity in the fuel. Simply stated, lubricity is that quality that prevents wear when two moving metal parts come in contact with each other in the fuel system. Since the introduction of low sulphur diesel fuel in 1993, there has been a considerable amount of effort by the automotive industry, users and the petroleum industry to incorporate a 'lubricity requirement' in commercial diesel fuel. This was a major issue in Europe, and a lubricity requirement is now included in the European CEN diesel fuel specifications and in the US ASTM specifications. In extreme cases, not specifying a lubricity standard for diesel fuel could lead to excessive wear and failure of diesel injection pumps. Bench methods to measure lubricity are available, and additives can be used to restore lubricity if needed. This effect depends on the severity of the hydro-treatment and is not linked specifically to a particular sulphur level, though it is generally NOT a problem for sulphur levels above 500 ppm.

- **Fuel system leaks.** Reducing sulphur tends to reduce levels of aromatics in diesel fuel. Large and sudden changes in aromatics can lead to fuel system leaks in older or poorly maintained vehicles (this has occurred in California, Australia and even Japan). The reason is that rubber and plastic components used in fuel systems swell in the presence of aromatics. Over time these components become 'set' in their swollen state, so that if the aromatics level is reduced, the components shrink causing leakage.
- **Static electricity.** A build-up of static electricity during filling of road or rail tankers can lead to generation of sparks in the ullage space above the fuel. This must of course be avoided through good handling practices, as it is a serious safety hazard. For neat gasoline the vapour space is too fuel-rich to allow an explosion, and for diesel it is too fuel-lean. However if switch loading of gasoline and diesel has taken place, it can be flammable and a spark may cause a devastating explosion. Reducing sulphur in fuels can reduce conductivity, making the need for safe handling and grounding procedures even more important.

A European Low Sulphur Loading Risk Study has now confirmed that there is an increased risk of electrostatic ignition when loading low sulphur (< 50 mg/kg) diesel fuel. Appropriate precautions must therefore be taken to minimize this risk, including reduction of loading speed or use of Static Dissipator Additive (SDA) in some circumstances, especially where the fuel conductivity is unknown. Since these risks are well known, Industry Guidelines [EU Model Code Part 21; ASTM D 5865-98] have been developed to essentially eliminate them, but they must be rigorously applied.

The way forward

This document aims to provide information to decision makers in developing countries around the world who are tackling the issues of improving air quality and reducing the related impact of vehicles emissions. IPIECA, its member companies, and its affiliated regional associations have provided here a compilation of know-how and expertise that draws on many years of tackling these issues in developed (primarily OECD) countries. The report attempts to discuss options and strategies that nations and regions might consider without assuming that the same solution is adequate everywhere.

The development of clean fuels and vehicles strategies has been a key issue in OECD countries for the past 20 years, or more, and it has led to considerable reductions in vehicle emissions. It is expected that the same issues will take central stage in developing countries over the next 10 years.

In the context of exploring the potential contribution of vehicle emissions to urban air quality the report provides a brief overview of the reduction potential attainable by advanced vehicle technologies and lower sulphur fuels. It is important to recognize the word 'potential' since both fuels and vehicle technologies are merely 'enablers'. To actually contribute to improving air quality these technologies need to be deployed into the 'on-road' vehicle fleets, and these advanced technologies need to be adequately maintained and their implementation enforced.

In considering the phase down of fuel sulphur levels, it is essential to analyse investment capital requirements and operating costs based on the configuration of local refineries, the prevalent sources of crude oil and the anticipated future specifications for products. It has been shown above that this analysis has to be coupled with an understanding of the emission reductions attainable with each level of fuel sulphur and its impact on the goal of attaining local air quality targets. It is in that context that final decisions will have to be made on the desired fuel sulphur level.

The next step in the strategy development is to assess the economics of both market- and technologies-led options, and develop coherent 'road maps' for implementation. It is important to underscore the fact that in OECD countries fuel production and marketing systems are typically operated by private industry. This is not the case in the developing world where governments assume a more active role in the production and distribution of energy products. Nonetheless, even 'public' enterprises cannot ignore commercial realities, and countries should not bankrupt themselves while trying to force the premature adoption of inappropriate and uneconomic technologies. At the same time, society should focus its financial resources to address needed improvements in air quality at a level that is commensurate with the severity of the problem and the need to protect human health and welfare.

IPIECA and its member companies hope to be able to continue to contribute to the ongoing global dialogue on these issues and provide additional expertise, as needed. On their part, IPIECA and its members will continue to improve the efficacy of refining technologies and will also work with all stakeholders to address issues that are more specifically within the 'public' domain. Such areas might include development of fuel and vehicle standards, inspection and maintenance programmes, scrappage of older vehicles, and appropriate technology retrofits, to name a few. Using these combined approaches for dealing both with new and in-use vehicles will ensure optimal strategies for emission reductions that are facilitated by the introduction of reduced sulphur in transportation fuels.

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Glossary

Atmospheric distillation
The refining process of separation of oil components at atmospheric pressure by heating to temperatures of 300–400 °C (600–750 °F) and subsequent condensing of the fractions by cooling.

ASTM
American Society for Testing and Materials: a standard-setting body for fuel properties and applicable test methods.

Barrel
A volumetric unit of measure used for crude oil, petroleum and petrochemical products. One barrel is equivalent to 42 US gallons, 35 imperial gallons or 159 litres.

Catalysis
The alteration of the rate of a chemical reaction by the presence of a 'foreign' substance (catalyst) that remains relatively unchanged at the end of the reaction.

Catalyst
A substance that aids or promotes a chemical reaction without forming part of the final product. It enables the reaction to take place faster or at a lower temperature and remains relatively unchanged at the end of the reaction. Nevertheless, in industrial processes, the catalyst must be replaced periodically to maintain economic production.

Catalytic reforming
A catalytic process of dehydrogenation and ring closure of gasoline components to raise the octane of the resulting gasoline. The hydrogen by-product is often used in the refineries for hydroprocessing.

Crude oil
The portion of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude oil may include small amounts of non-hydrocarbons produced with the liquids.

Diesel
'Diesel' is the common name for automotive gasoil—see '*Gasoil*'.

Distillate fuel
A general classification for one of the petroleum fractions produced in the conventional distillation operations, notionally boiling between 175–350 °C (350–650 °F). It is used primarily for on- and off-road diesel engine fuel, space heating and electric power generation. Included are products known in the USA as No. 1, No. 2 and No. 4 fuel oils; and No. 1, No. 2 and No. 4 diesel fuels.

EGR
Exhaust gas recirculation

Feedstock
Material that is fed into a processing unit. The term covers both raw materials and crudes and intermediates. It can also cover base oil and additives, although these could be the output product from some processes.

Fluid catalytic cracking
The refining process of breaking down the larger, heavier and more complex hydrocarbon molecules into simpler and lighter molecules. Catalytic cracking is accomplished by the use of a catalytic agent and is an effective process for increasing the yield of gasoline from crude oil.

Gasoil
Middle distillate fraction of which not more than 50 per cent by volume distills at temperatures lower than 240 °C (460 °F) and more than 50 per cent by volume distills at temperatures lower than 340 °C (640 °F).

Hydrocarbon
A class of organic chemical compounds composed of hydrogen and carbon that could be in either the gaseous, liquid or solid phases at ambient conditions. The molecular structure of hydrocarbon compounds varies from the simplest (e.g., methane, a constituent of natural gas) to the heavy and complex, such as in crude oil.

Hydrocracking
A process used for converting a vacuum distillate into transportation fuels, e.g. gas oil, over a catalyst and under a high temperature and hydrogen partial pressure, and is an effective process for increasing the yield of diesel and jet fuel from crude oil.

Hydroprocessing
A refining process that uses hydrogen and catalysts with high pressure for converting middle boiling or residual material to high octane gasoline, reformer charge stock, jet fuel and/or high grade fuel oil. The process uses one or more catalysts, depending upon product output, and can handle high sulphur feedstocks without prior desulphurization.

Hydrotreating
Processes that convert or remove undesirable components with the use of catalysts and hydrogen; includes HDS (hydrodesulphurization) which refers to the removal of sulphur.

I&M
An abbreviation for 'Inspection and Maintenance' of vehicles, a standardized programme of vehicle inspection designed to certify vehicles annually (or periodically) in terms of their roadworthiness/safety and their environmental performance. Usually implemented by government authorities.

Kerosene
Distillate fraction of which more than 50 per cent by volume distills at a temperature lower than 240 °C (460 °F).

Motor gasoline (finished)
A complex mixture of volatile hydrocarbons, with or without small quantities of additives, that has been blended to form a fuel suitable for use in spark-ignition engines. 'Motor gasoline' includes reformulated motor gasoline, oxygenated motor gasoline, and other finished motor gasoline.

Naphtha
Term usually restricted to a class of colourless, volatile, flammable liquid hydrocarbon mixtures. Obtained as one of the more volatile fractions in the fractional distillation of petroleum (when it is also known as petroleum naphtha).

NLEV
National Low Emission Vehicle Program (USA)

NO_x
Oxides of nitrogen; primarily including the sum of nitric oxide and nitrogen dioxide ($NO + NO_2$).

Octane
A measure of the detonation quality of gasoline; the higher the octane number, the higher the resistances to engine knock.

Off-road diesel
A fuel generally used for farm, construction, marine and railroad purposes.

On-road diesel
A fuel used for road transportation purposes by automobiles, trucks and buses primarily.

Oxygenates
Any substance which, when added to gasoline, increases the amount of oxygen in that gasoline blend.

Particulate matter (PM)
Inclusive term used to designate suspended solid particles and liquid droplets that are found in emission sources and in the ambient atmosphere. Particulate matter is normally classified by its size, e.g. PM_{10} refers to particles with average diameter not exceeding 10 micrometers.

PPM
Parts per million; could be designated either by weight or by volume.

Residual fuel oil
The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. This oil is used for commercial and industrial heating and electricity generation, and to power ships.

Segregated batch
A quantity of product that is not co-mingled with any other product batch; the shipper receives the same molecules sent. This can be necessary because of unique product characteristics or environmental considerations.

Straight-run
A description that applies to a product of crude oil that has been made by distillation with no chemical conversion.

Sulphur
A yellowish, non-metallic element, sometimes known as brimstone, that occurs naturally in crude oil.

Transmix
The interface that occurs between batches of incompatible product grades and that cannot be absorbed into adjacent batches.

Ultra-low sulphur
In the USA 'ultra-low sulphur' is taken to mean <15 ppm, and in Europe <50 ppm, while 'sulphur-free' is generally taken to mean <10 ppm sulphur. In this document 'ultra-low sulphur' means <50 ppm and 'sulphur-free' means <10 ppm sulphur.

Supplementary Document A:

Diesel emissions reduction in Asian cities (a case study)

Background

Many National and city governments in Asia are taking a growing interest in air quality, as many cities suffer from high levels of pollution. In response to this situation, a number of organisations have established a 'Clean Air Initiative for Asian Cities' (CAI-Asia)[1]; to develop a more structured exchange of information and experience across Asian countries. This initiative is sponsoring different studies assessing air quality in various Asian cities and looking for strategies to reduce emissions. One such study was undertaken by Enstrat International Ltd with the goal of better understanding current emissions from diesel fuelled vehicles and options for their reduction [Enstrat, 2004].

The study looked at three specific cities, Bangkok, Bangalore and Manila, using the IPIECA emission inventory model [IPIECA, 2001], also known as the IPIECA Toolkit. The model is based on European vehicle emissions factors as used in the current Clean Air For Europe (CAFE) programme[2]. As most vehicles in Asian cities are of Japanese origin, but similar to the size and type of vehicles sold in Europe, this model is appropriate for these cities. Moreover, detailed vehicle population data that is needed for the model was available for these three cities, along with average annual vehicle mileage, broken down into urban, sub-urban and highway driving and including average speeds for each driving mode. Assumptions were made for the growth and replacement of the vehicle population up to 2020.

The model allows the simulation of different levels of vehicle emission control by using appropriate emission factors. Fuel quality effects, including sulphur at levels below 500 ppm, were simulated using equations developed in the EPEFE programme [EPEFE, 1999]. To simulate the effect of higher sulphur levels on particulate emissions, it was assumed that 3% of fuel sulphur would form sulphate (a compromise

[1] www.cleanairnet.org/caiasia/1412/channel.html
[2] COPERT III database issued in November 2000

between US and European data suggesting 2% and 4%, respectively). The effect of advanced Inspection and Maintenance (I&M) schemes was simulated by reducing numbers of high emitters and reducing the degradation of emissions performance of vehicles with time, which is inbuilt into the model. Sensitivity studies were also made for parameters such as kilometres driven, traffic speed and fleet growth.

Hypothetical city simulated

In addition to the three specific cities, all of which have implemented some level of vehicle emissions and fuel quality control based on EU legislation, the study also developed an inventory for a 'hypothetical' Asian city based on vehicle populations that are consistent with those from the three known cities, but with no emission controls in place. Such a hypothetical city can be used to compare the effects of:

- introducing new vehicle emission controls at various levels;
- fuel sulphur reduction;
- implementation of an Inspection and Maintenance scheme.

To compare these effects, we can look at total mass emissions of NO_x and particulate matter (PM) from the diesel fleet in 2020, after substantial vehicle population growth to 2 million vehicles (of which 800 000 are diesel), with various emission controls being introduced in 2005. Figure A1 presents the breakdown of this hypothetical vehicle fleet.

Discussion of results

Figure A2 compares the effects of reducing fuel sulphur content, implementing European Emission limits and I&M schemes. Note that the cases marked 'none' and Euro I emission controls are the 'Base Cases' and all vehicles are at these levels to start with. The other cases assume introduction of different emissions limits with all of them assumed to start in 2005, with subsequent growth of numbers of these emission-controlled vehicles.

This clearly shows that reducing sulphur alone from 5000 to 50 ppm has little effect on emissions, less than 5% for vehicles with no emissions controls, whereas introducing Euro II or Euro III vehicle emission controls, together with reduced sulphur to enable them to operate effectively, will reduce NO_x emissions by more than 60%. Introduction of an I&M scheme provides a small additional benefit.

A similar picture can be seen for PM emissions as shown in Figure A3. Because around 30% of PM is sulphate, reducing sulphur, especially from 5000 ppm to 500 ppm does give a significant reduction in total PM. There is an overall reduction

Figure A1: Vehicle Population of hypothetical Asian city in 2020

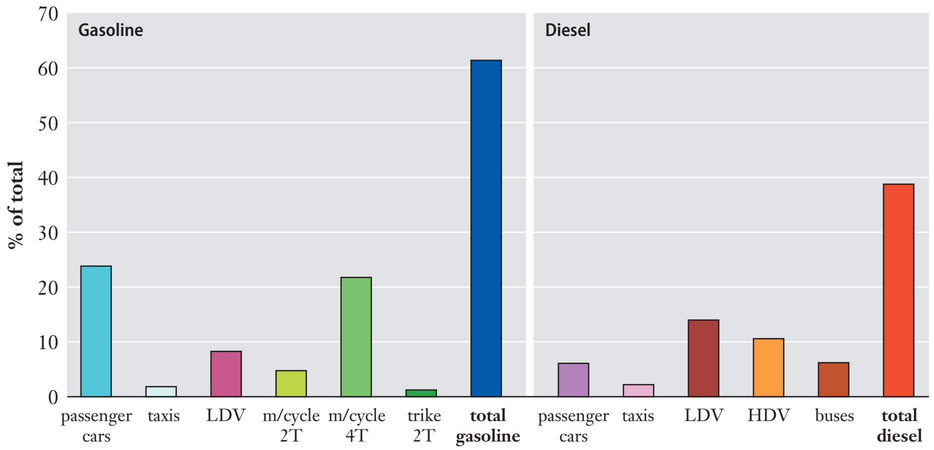
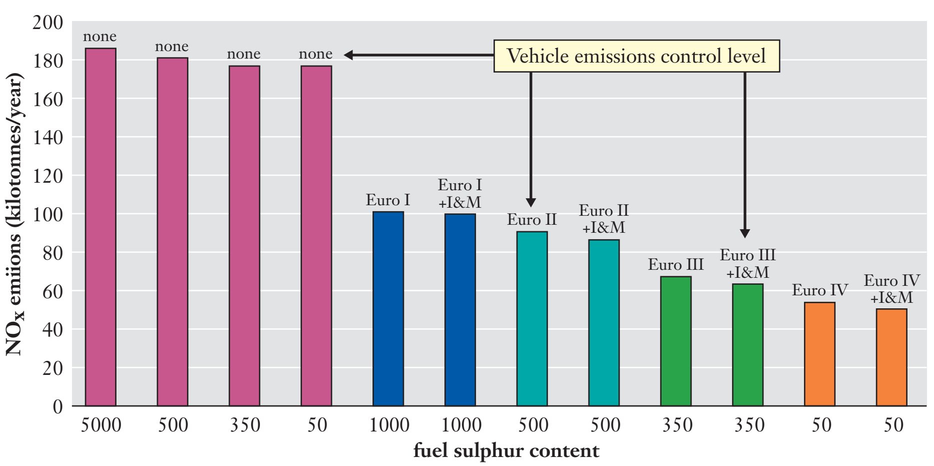


Figure A2: Effects of vehicle emissions controls, fuel sulphur content and I&M on NO_x Emissions from a hypothetical Asian city in 2020

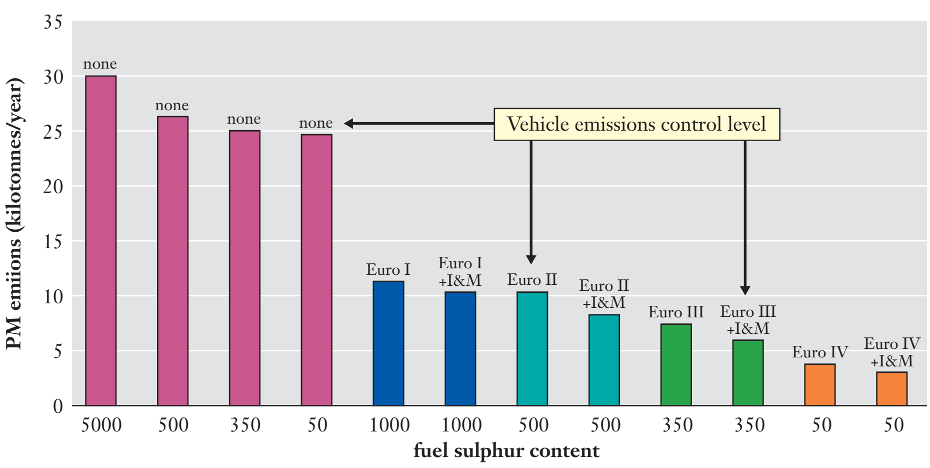


of 18% from the base case to 50 ppm, but most of the benefit (13%) comes from the initial reduction to 500 ppm. However, once again the major reduction in emissions comes from introduction of vehicle emission controls, e.g. Euro III with 350 ppm S would reduce emissions by 75%. Introduction of an I&M scheme would reduce emissions by a further 5%.

Conclusions

These hypothetical emission inventory calculations are examples of what should be done for any city or country where emission control is under discussion, though of course emissions from gasoline vehicles and other sources must also be considered. What should be emphasized for many Asian cities is that emissions from motorcycles and 3-wheelers (with both 2-stroke and 4-stroke engines) might contribute significantly to total emissions though they are not usually included in technology evaluations that rely on European or US emission standards. Nonetheless, what is clear from this study, and other similar studies in other parts of the world, is that reducing fuel sulphur content without introducing corresponding vehicle emission limits gives only very small reductions in emissions from this sector.

Figure A3: Effects of vehicle emissions controls, fuel sulphur content and I&M on PM Emissions from a hypothetical Asian city in 2020



Supplementary Document B:

Matching vehicle emission control technologies with fuel sulphur

Gasoline vehicles

The primary pollutants of concern from gasoline-fuelled vehicles are carbon monoxide, hydrocarbons and oxides of nitrogen. Vehicles introduced in the mid 1970s in the USA and Japan had simple oxidation catalysts that oxidized unburned CO and HC but did not control NO_x. Some **oxidation catalysts** were used as retrofits in a number of European countries in the early 1980s.

Three-way catalysts were first introduced in the early 1980s and have since been almost universally applied to control gasoline vehicle emissions. In addition to the oxidation of CO and HC, the 3-way catalysts use some of the unburned CO and HC to convert NO_x back to nitrogen. This means they must work at exactly the stoichiometric (chemically correct) air/fuel ratio, where conversion efficiency is well over 90%. Three-way catalysts have undergone significant improvements in efficiency and durability over the years. Indeed the latest catalyst systems produce very low emission levels and are certified in the USA as Super Low Emission Vehicles (SULEVs). To achieve these levels requires an advanced catalyst, accurate fuel injection and a sophisticated electronic engine control system.

Sulphur has been likened to lead in gasoline because it degrades the performance of catalysts. There are important differences however in that the effect of sulphur is reversible while that of lead is not. Lead in gasoline degrades catalyst (3-way and oxidation) performance severely and irreversibly. Unlike lead, sulphur in gasoline reduces the efficiency of conventional catalysts to convert CO, HC and NO_x by a few percent. However, this reduction in conversion efficiency can be fully reversed by running the catalyst under hot, fuel rich conditions (i.e. high speed driving) on low sulphur fuel.

The effect of sulphur on emissions from vehicles with 3-way catalysts has been studied in a number of test programmes. In the European EPEFE program lowering gasoline sulphur content from 382 mg/kg to 18 mg/kg achieved a linear reduction in CO, HC and NOx emissions of 8–10% over the European test cycle [EPEFE, 1995].

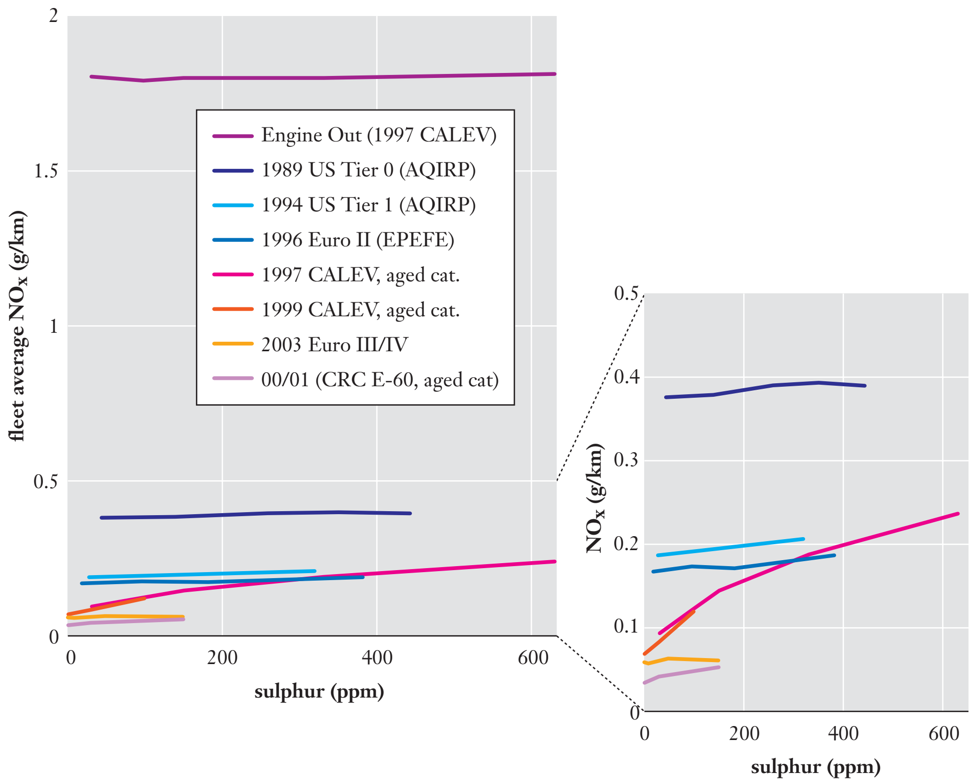
Several programmes have been carried out in the USA, including the Air Quality Improvement Research Program (AQIRP) that focused on late 1980s technology vehicles. The AQIRP showed that a reduction in gasoline sulphur levels from 450 mg/kg to 50 mg/kg lowered exhaust emissions by 10–15% [Benson, 1996]. More recent test studies were conducted on 1997 model year low emission vehicles (LEVs) followed by an extension to 1999 model year LEVs [Schleyer, 1998]. The fleet average results from these 1997 and 1999 California vehicles showed a stronger percentage response to fuel sulphur than the earlier test fleets, especially for NO_x.

This was widely interpreted as meaning that sulphur sensitivity would increase at lower emission levels. However, an analysis by CONCAWE showed that the California LEV fleet results were strongly influenced by a small number of higher emitting light trucks that exhibited a very strong sulphur effect. Many of the other LEVs showed very low sensitivity to sulphur. Recent data from Europe [Rickeard, 2003] and the USA [CRC, 2004] show that the newest vehicles are no more sensitive to sulphur than the older technology. A full analysis of the response of emissions to fuel sulphur is contained in a recent SAE paper [Hochhauser *et al.*, 2006], That paper discusses other issues such as catalyst age, reversibility, impact of sulphur on inspection maintenance programmes, and long-term effects. Figure B1 shows the impact of sulphur on exhaust emissions from a wide range of US and European vehicle technologies spanning the years 1989 through 2001. For simplicity and brevity, the figure focuses on NO_x, although the trends are similar for HC and CO. The figure clearly shows that the largest emission reductions are obtained when going from uncontrolled engine-out emissions to a 3-way catalyst controlled exhaust, enabled by removal of lead from gasoline. Further small reductions in emissions (CO, HC, NO_x) can be achieved with a reduction in sulphur content. It also shows that the 1997 and 1999 LEV studies show much higher sulphur sensitivity than other programmes, due (as noted above) to the impact of a few very sensitive vehicles.

Gasoline sulphur levels have been reduced to 30 (USA) and 50 (Europe and Japan) mg/kg to allow the latest low emission (US Tier 2, Euro 4) vehicles to work at highest efficiency. However it is clear that these advanced 3-way catalysts still will work satisfactorily, albeit with slightly reduced efficiency, at relatively high sulphur levels, up to 500 ppm.

In 2005, Europe and Japan further reduced sulphur to 10 ppm, to enable more fuel-efficient **Lean Burn Direct Injection Spark Ignition** (LDI) engines that are aimed at improving fuel economy and reducing CO_2 emissions. Such engines require

Figure B1: Effect of sulphur content on NO_x emissions from gasoline engines: comparison of a range of studies



aftertreatment devices that operate under lean air/fuel ratio conditions where a conventional 3-way catalyst will not control NO_x emissions. Many of the aftertreatment systems being developed for LDI (lean NO_x catalysts or traps) are extremely sensitive to sulphur and require essentially sulphur-free fuel. The main reason to require sulphur-free gasoline (<10 ppm S) in Europe and Japan was to facilitate the introduction of this technology. However LDI is only one of many technologies that can improve fuel economy, and recently LDI penetration has essentially stopped in Europe and Japan because it is less cost effective than other technologies. It is now doubtful whether LDI technology will spread outside of Europe and Japan, especially as it has not yet been able to achieve the extremely low emission levels that have been achieved by 3-way catalysts operating at stoichiometric

Table B1: Gasoline vehicle emission control systems

Emission limit	Control system	Features	Usage	Effectiveness CO	Effectiveness HC	Effectiveness NO_x	Sulphur effect	Fuel economy	Regulatory S limit (mg/kg)	Appropriate S limit
EU-ECE pre-1990 US pre 1975	No controls	No emissions control other than engine design features. Engine can run lean at part load.	US and Japan before 1975, Europe before mid 1980s.	0	0	0	No effect.	0	1000	1000
US CAA 1975 Japan 1975	Oxidation catalyst	Oxidizes CO and HC. Engine can run lean at part load.	US and Japanese cars in 1970s and early 80s. Some European retrofits.	✓	✓	0	Sulphur will reduce conversion efficiency, but no data available on size of the effect.	0	1000	500–1000
Euro I–III US CAAA Tier 1 Japan 1978	3-way catalyst	Oxidizes CO and HC, simultaneously reduces NO_x. Works only at exactly stoichiometric air/fuel ratio. Needs oxygen sensor, fuel injection and electronic engine control system to accurately control air/fuel ratio.	Used universally on all gasoline engines in USA, Japan and Europe since mid/late 1980s, and in many other countries.	✓✓	✓✓	✓✓	Manufacturers recommend 500mg/kg S max—usage above this level is common, however increasing sulphur will reduce catalyst efficiency. Many studies show different effects: EPEFE showed 10% increase in emissions for 382 vs 18 mg/kg S.	–	EU 500 US 1000 EU-3 150	500+
Euro IV US Tier 2, LEV, SULEV	3-way catalyst	As above, also with OBD, to self-diagnose faults.	US and Europe from 2004–5.	✓✓✓	✓✓✓	✓✓✓	Some US studies have showed greater sulphur effects on LEVs, but most recent work shows modern low emission vehicles are no more senstive to sulphur and work well at higher sulphur levels.	–	US 30 EU 50	150–500
Euro III–IV Japan 1978	NO_x storage catalyst	Catalyst oxidizes CO and HC while engine runs lean, and stores NO_x as nitrate inside catalyst. Periodically engine must run rich for few seconds when CO and HC are used to reduce nitrate to nitrogen and regenerate catalyst.	New generation lean burn direct injection (LDI) engines in Japan and Europe.	✓✓	✓✓	✓✓	Very sensitive to S. Catalyst will absorb SO_2 in preference to NO_2, as sulphate builds up, NO_x control efficiency reduces dramatically. Catalyst can be regenerated by running very hot and rich, but this reduces fuel economy benefit. Needs sulphur free fuel for best performance.	✓	10	Not recommended for developing countries. Technology not widely available.

air-fuel ratios (SULEVs). Developing countries could learn from LDI experience in Europe and Japan and avoid adopting such emerging technologies that require new fuels until they are widely available.

Table B1 lists the various different technologies applied to gasoline engines, and summarizes their effectiveness, their sensitivity to fuel sulphur, and gives 'appropriate' sulphur levels for developing countries who wish to introduce such technology.

It is possible, in principle, to fit an oxidation catalyst onto an existing non-catalyst vehicle, and this was done to a limited extent in some European countries in the late 1980s. These systems provided substantial reductions in CO and HC emissions. However 3-way catalysts cannot be retrofitted because of the need for complex sensors, electronic controls and electronic fuel injection systems to control the air/fuel ratio. Thus retrofitting 3-way catalysts to older technology gasoline engines is not a realistic proposition.

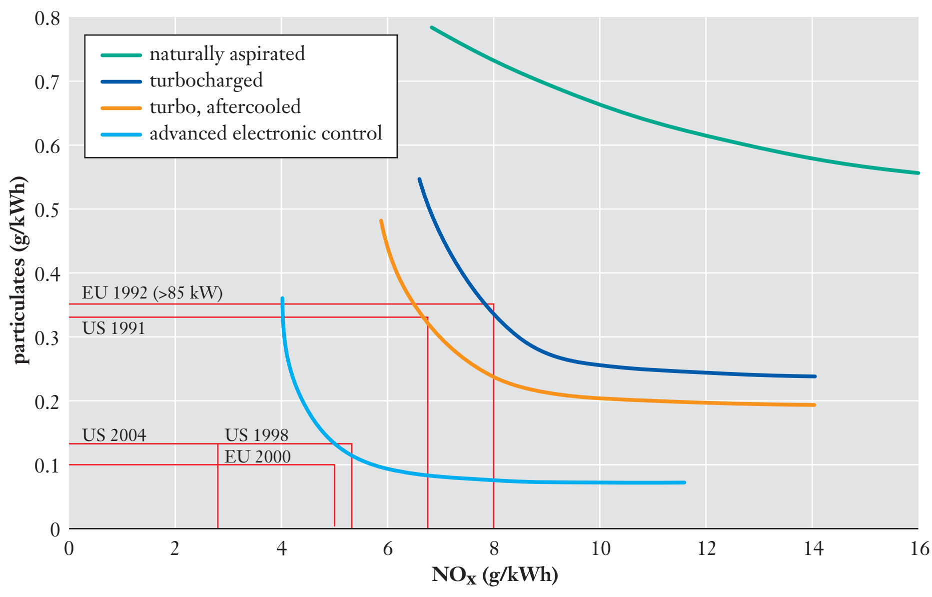
For gasoline vehicles with no catalytic converters, reducing sulphur will have no effect on CO, HC or NO_x emissions. While the amount of SO_2 emitted is in direct proportion to the amount of sulphur in the fuel, gasoline vehicles are not a significant source of SO_2. Reducing sulphur does give minor benefits by reducing the acidity of exhaust gas, so exhaust systems will last slightly longer, but this will not significantly affect emissions.

Diesel vehicles

Diesel engines are more efficient than gasoline engines as they operate at a higher compression ratio, without throttling and at lean air/fuel ratio, so CO_2 emissions and fuel consumption are lower. In addition diesel fuel has ~10–15% greater density than gasoline, so fuel consumption by volume is even lower. For these reasons diesel engines are used in virtually all trucks and buses throughout the world. Recent developments in technology (and often favourable government tax incentives) have made diesel passenger cars very attractive in Europe with around 50% of new cars being diesel powered. Some other regions in Asia and South America also have major diesel light-duty fleets, including diesel taxis and passenger cars and light trucks in fleet service, but the personal passenger cars have not moved to diesel engines to the same extent as in Europe.

Without any pollution controls, diesels produce very low emissions of CO and HC, but NO_x and especially particulate matter (PM) emissions are much higher than for gasoline engines with catalysts. There is always a design trade-off between NO_x and PM emissions at any level of engine technology, as shown in Figure B2, such that engine modifications to reduce PM will increase NO_x and vice versa. However, reducing PM also improves fuel consumption, so there is an incentive to optimize engines with low PM/high NO_x and use aftertreatment devices to reduce the NO_x. Diesel fuel has the added benefit of low volatility, which virtually eliminates evaporative HC emissions.

Figure B2: Heavy-duty diesel engine settings: emission trade-off at different technology levels



Sulphur will have no effect on emissions of CO, HC and NO_x for diesel vehicles without emission control systems; however, there is an effect on PM emissions for the following reason: fuel sulphur is combusted in the engine and forms sulphur dioxide (SO_2), with some (typically 2–3%) being further oxidized to sulphur trioxide (SO_3), which reacts with water to form sulphuric acid and other sulphate salts. These condense on to the carbonaceous particulate matter that is emitted. In fact diesel exhaust particulate matter (PM) emissions are made up of three constituents:

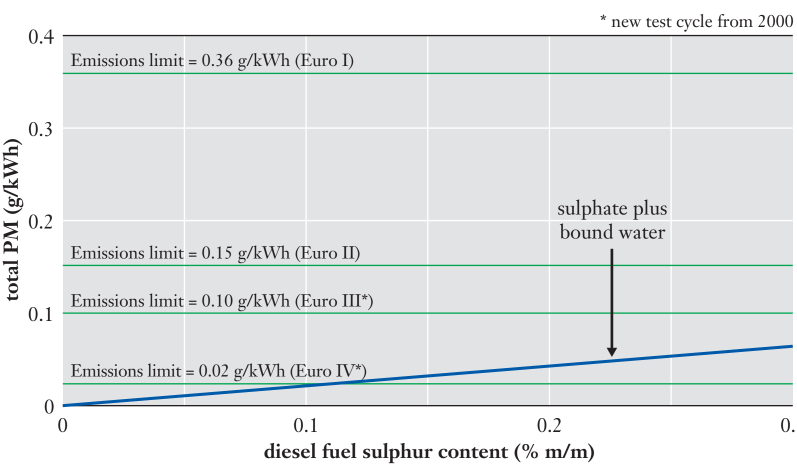
i. solid carbon particles (soot) derived from unburned fuel;
ii. liquid hydrocarbons adsorbed on the carbon from partially burned fuel and lubricant, also known as the Soluble Organic Fraction (SOF); and
iii. sulphates adsorbed on to the surface as described above.

The relative amounts of the three constituents are a function of engine technology and fuel sulphur levels.

Figure B3 shows the contribution of sulphur at different levels to PM from heavy-duty engines for different European emission limits. For EURO I (1992) engines with no emission controls, the contribution of sulphur as sulphate is minor. However at EURO IV (2005) levels, the sulphate from a fuel with 0.1 %m/m sulphur would meet or exceed the emission limit, without any carbon! This is one reason why lower sulphur levels are needed for low emission engines. In Europe, the sulphur limits set were 0.2% for EURO I, 500 ppm for EURO II, 350 ppm for EURO III and 10 ppm for EURO IV. This is also the reason that sulphur was reduced from 0.5% to 0.05% in US diesel in 1991.

In addition, fuel sulphur contributes to total SO_2 emissions, though it should be recognized that most SO_2 in urban areas is from stationary sources. All the SO_2 emitted to the ambient atmosphere can lead to secondary particle formation—

Figure B3: Contribution of fuel sulphur to PM emissions from European heavy-duty diesel engines



sulphate plus water = (%fuel sulphur/100) x fuel consumption x (sulphate conversion factor/100) x 98/32 x 2.3

particles that form through a complicated set of reactions during long-range atmospheric transport.

Significant emission reductions have been achieved by **engine modifications** without expensive aftertreatment devices. High pressure fuel injectors—either common-rail or unit injectors—improve atomization and combustion efficiency. Injector pressures have been rising continuously since the early 1900s. New engines employ pressures as high as 2000 bar with multiple injections per cycle and use sophisticated Engine Management Systems to control the number, timing and duration of injections. Modern engines also have pistons and combustion chambers that are designed for complete combustion and low emissions over the entire operating range.

Nitrogen oxides (NO_x) emissions can be substantially reduced by use of **Exhaust Gas Recirculation (EGR)**. This technique is widely used on gasoline engines and functions by lowering the peak combustion temperature, which controls NO_x formation. EGR systems are not sensitive to sulphur but do need low PM emissions to prevent the EGR control valve from clogging.

Many light-duty diesel vehicles are now fitted with **oxidation catalysts**, which help to reduce PM emissions. Oxidation catalysts work by oxidizing the SOF fraction of PM; they also reduce gaseous HC and CO emissions. They are only effective if the catalyst is above its 'light-off' temperature, which is around 200 ºC. However if the exhaust temperature gets too high (above around 350 ºC) then more of the SO_2 will be oxidized to sulphate PM when compared to a vehicle without an oxidation catalyst. Therefore, exhaust temperature and positioning of the catalyst is critical, and lower sulphur fuels are essential for effective operation. Diesel fuel with a 500-mg/kg sulphur content (500 ppm) was introduced in Europe to allow use of oxidation catalysts to meet EURO II emission limits. The 500-mg/kg sulphur level has been widely adopted around the world to allow use of modern emission-controlled light-duty and heavy-duty diesel engines.

Particulate traps are very effective and can reduce PM by more than 95%. However, the traps are essentially filters and clog if not regenerated. A number of approaches have been adopted for regeneration as summarized in Table B2. This is an area of extensive development and many strategies for regenerating traps are being tested in a variety of applications. The traps themselves, if thermally regenerated, are not especially sensitive to sulphur. However, when combined with a catalyst to oxidize soot, they become more sensitive to sulphur since sulphur in the exhaust is oxidized to sulphate PM that increases overall PM emissions. More complex systems, such as the continuously regenerative trap (CRT) for heavy-duty engines, are very effective but sensitive to sulphur and require fuels with a level of 50 mg/kg sulphur or less. Another type of trap using a catalyst dissolved in the fuel is widely used in some light-duty engines in Europe, and gives very low PM emissions on fuels containing up to 350 mg/kg sulphur [Schaefer, 2003].

NO_x storage catalysts, operating on the same principle as for lean-burn gasoline engines (see above), are being developed. However, it is much harder to get a diesel engine to run rich to regenerate the catalyst, without producing large amounts of particulates. Thus these systems are complex, expensive and their long-term durability remains to be proven. If they ever are developed for commercial use, they will almost certainly require 15-mg/kg sulphur fuels to work effectively.

Another approach to reduce NO_x is **Selective Catalytic Reduction (SCR)**. This requires injection of ammonia into the exhaust stream, which reacts with NO_x over a catalyst and reduces it to nitrogen. These systems are very effective and have been widely used for stationary engines and boilers etc. Developing systems to work on diesel trucks with their rapid changes in load is more difficult, but has been achieved and introduced in Europe. While ammonia was initially considered for injection, industry agreement has now been reached to use a liquid urea solution, where the urea is converted to ammonia by another catalyst in the exhaust. The SCR system itself is not sensitive to sulphur so it can work on 500-mg/kg fuels. However, more advanced systems use extra oxidation catalysts before (to convert NO to NO_2 which reacts better with ammonia) and after (to control ammonia emissions) the main catalyst. These are sulphur sensitive, so advanced SCR systems are likely to need 50-mg/kg max sulphur fuel.

As discussed above, engines can be designed to give high NO_x emissions with low PM, and use NO_x emission control, or to give low NO_x but high PM, and use a PM trap. The former approach results in a more efficient engine with better fuel economy (and lower CO_2 emissions per distance traveled). For example use of SCR deNO_x to meet EURO IV emission limits gives 5–10% better fuel economy than a low NO_x engine with a PM trap. As emission limits are reduced to very low levels however, it is likely that both NO_x and PM control may be needed, and combined '4-way' systems are being developed, such as the Toyota DPNR (Diesel Particulate-NO_x Reduction) system.

Table B2 lists the various different technologies applied to diesel engines, and summarizes their effectiveness, their sensitivity to fuel sulphur, and gives 'appropriate' sulphur levels for developing countries who wish to introduce such technology.

Inspection & Maintenance (I & M) schemes

A targeted and effective vehicle inspection and maintenance programme is necessary to sustain the emissions reduction from the above engine and aftertreatment technologies. Figure B1 shows that if three-way catalysts are not working properly, it is easy to increase the NO_x emissions from the base of 0.1 to 0.4 gm/km to engine out NO_x levels of 1.8 gm/km.

The latest emission controlled vehicles in the USA and Europe are required to be fitted with on-board diagnostic (OBD) systems that monitor the performance of emission control devices and warn the driver when there is a problem. OBD systems must monitor operation of the catalyst and oxygen sensor for gasoline engines and detect misfires. For diesels OBD must monitor catalyst and/or trap operation, plus fuel injection. Electronic control systems must be checked for both gasoline and diesel engines. These systems are effective, but very complex and require skilled technicians with diagnostic computers to establish what the malfunctions are, and what repairs are needed to correct them. In the USA and in Europe, I&M programmes monitor the performance of vehicles equipped with OBD systems to help ensure that motorists have taken corrective action when OBD warning lights are illuminated. If OBD-equipped vehicles are used in developing countries, similar measures would need to be put in place to encourage proper driver response to warning light illumination.

The subject of I&M is well reviewed in a recent World Bank Report [World Bank, 2004], which discusses the issues involved. Experience in Mexico City and elsewhere has shown that large centralized test-only centres work better than decentralized test-and-repair garages that are more open to fraud. In some circumstances, targeted incentive schemes for scrappage or replacement of high mileage gross polluters may be considered for complementing I&M programmes.

The practices outlined by World Bank for effective I&M can be further enhanced using 'remote sensing' technology to identify vehicles which are high emitters. Remote sensing measures emissions from a large number of vehicles operated under a snapshot of real world driving conditions. This technology uses an infrared beam

Table B2: Diesel vehicle emission control systems

Emission limit	Control system	Features	Usage	Effectiveness CO	HC	NO_x	PM	Sulphur effect	Fuel economy	Regulatory S limit (mg/kg)	Appropriate S limit (mg/kg)
EU-ECE Euro I US pre-1998	No emission control system	No emissions control other than engine design features.	LD engines prior to 1996 in EU and USA, most current HD engines.	0	0	0	0	No effects on gaseous emissions, small increase in sulphate PM emissions.	0	2000–5000	2000–5000
US 1991	Engine modifications	High pressure computer controlled unit injectors, improved piston and combustion chamber design	US heavy-duty diesels	✓	✓	✓	✓	No effects on gaseous emissions, small increase in sulphate PM emissions	0	5000	5000
US 1994 Euro II–IV HD	Engine modifications, Exhaust Gas Recycle (EGR)	Improved injectors, aftercooled turbochargers. The cooled EGR gas has a higher heat capacity than air, contains less oxygen and lowers the combustion temperature thereby lowering NO_x formation. EGR can reduce NO_x by up to 40%.	US heavy-duty diesels	✓	✓	✓	✓	No effects on gaseous emissions, small increase in sulphate PM emissions	0	500	500
Euro II–III LD 1996–2005	Oxidation catalyst (Oxicat)	Oxidizes CO and HC only. Reduces PM emissions by oxidizing Soluble Organic Fraction (SOF) at exhaust temperatures over 200 °C, but below 350 °C.	EURO II light-duty vehicles since 1996. Some European retrofits .	✓	✓	0	✓	Oxicats also can oxidize SO_2 to SO_3, which reacts with water and other materials to form sulphates, which condense on and increase PM emissions. Thus fuel with < 500 mg/kg S is needed.	0	EU2 500 EU3 350	500
Euro IV–V 2005 on	Diesel Particulate Filters (DPFs)	Reduce PM emissions by filtration, generally with a porous ceramic filter similar to an oxicat but with opposing ends of passages blocked so that exhaust flows *through* the walls. Filtration efficiency is very high, the problem is cleaning or regenerating the DPF. The simplest approach is to burn off the PM by electric heating, a fuel burner or late fuel injection.	Not widely used due to complexity and durability problems. High temperatures generated during regeneration cause ceramic filter to fail.	0	0	0	✓✓	No specific effects of sulphur, but sulphate in the trap is not burnt off. Traps need to be regenerated or physically cleaned at service intervals. Energy input increases fuel consumption and CO_2. Low sulphur fuels are required.	–	500	500

across a road to take near instantaneous readings of emissions from a gasoline vehicle immediately after it passes through the beam 'line-of-sight'. High emitters can be pulled over, or digital pictures taken showing vehicle registration number, for subsequent recall. Up to 4000 cars per hour can be measured by such a system.

Supplementary Document C:

Crude oil characteristics and expected product yields

Chemical composition of petroleum

Petroleum, also known as crude oil, is a complex mixture consisting of paraffin, naphthene (cycloparaffin) and aromatic hydrocarbons, as well as nitrogen-, oxygen- and sulphur-containing compounds, traces of a variety of metal-containing compounds, and inorganic compounds. All in all, probably more than a thousand compounds make up 'raw' petroleum. Among the most important compound classes are:

Hydrocarbons

Contain chains of carbon and hydrogen in various proportions and configurations, and are subdivided into:

- **Saturated** normal alkanes (n-alkane) and iso-alkanes (i-alkane)—these are characterized by the general formula of CnH_2n+2, and with increasing boiling points and densities with increasing numbers of carbon (C) atoms. The branched (iso-alkanes) are typically small in quantity, and the boiling point of straight chains is greater than iso-alkanes with the same number of C atoms.
- **Naphthenes** or cycloparaffins (saturated cyclic hydrocarbons i.e. cyclohexane)—these are characterized by the general formula CnH_2n for one-ring compounds.
- **Alkenes** or olefins—these consist of unsaturated aliphatic hydrocarbon (i.e. ethylene or propylene). Their initial quantity in crude oil is very small and they are normally produced during refining.
- **Aromatics** hydrocarbons (cyclic and polyunsaturated hydrocarbons containing conjugated double bonds)—these include alkylaromatics that have very high octane numbers, and polycyclic aromatic hydrocarbons, which contain more than one ring.

Heteroatom compounds

Contain atoms other than carbon and hydrogen in the compound chains. Some of the key compound classes include:

- Sulphur compounds might be present in inorganic and organic forms. In crude oils sulphur concentration can range widely as discussed further below. From some of the organic sulphur compounds—such as dibenzylthiophene (two benzene rings separated by one S atom)—it is most difficult to release the sulphur.
- Oxygen compounds are responsible for petroleum acidity; in particular when carboxylic or phenolic compounds are present.
- Nitrogen compounds consist of compounds such as carbazole (neutral) or quinoline (two benzene rings with one N atom on one ring).
- Metals (e.g. Ni, V, Fe) are present sometimes in the form of organo-complexes.

Crude oil classification

The most important classification of crude oil is by specific gravity (or density). High API gravity (low density) crude oils yield high volumes of gasoline and diesel fuel components, but low volumes of residual fuel oil. Low API gravity crude oils yield high volumes of gasoline and diesel fuel components, but high volumes of residual fuel oil.

Crude oils are also classified as low sulphur content (<0.5 Wt.%, or 5000 ppm), intermediate sulphur content (0.5 to 1.0 Wt.%, or 5000–10 000ppm), and high sulphur content (>1.0 Wt.%, or 10 000ppm). In general the definition of 'sweet crude' is one that does not contain hydrogen sulphide and has below 0.5 Wt.% sulphur content, and with only a minor portion of the sulphur content being present as mercaptans. Mercaptans (organic sulphur compounds) are the most malodorous contaminants of crude oil and petroleum products. Crude oils can also be classified by their predominant type of molecule, such as parafinic or naphthenic.

Table C1 provides examples of the characteristics for a range of crude oils from different regions of the world. The table shows typical Sulphur content of the listed crudes, and the expected yields and sulphur distribution in the various distillation fractions made from them in the refinery.

In the refinery process crude oil is converted into many products such as liquefied petroleum gas (LPG), gasoline, aviation and diesel fuels and others, as shown in Figure C1 for various regions of the world. The relative proportions of finished products produced will depend on the crude oil characteristics, the design of the refinery processes, and the strategy adopted by a given refinery to meet regional/local

Supplementary Document C: Crude oil characteristics and expected product yields

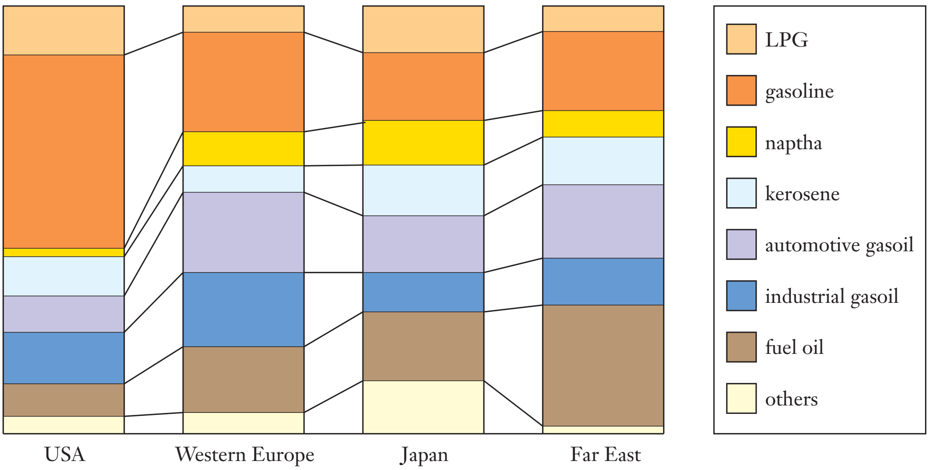
Table C1: Characteristics and yields of selected crude oils

	Sweet crude oil		Medium sulphur crude oil		High sulphur crude oil	
	High gravity (Bonny Light)	Low gravity (Bonny Medium)	High gravity (Murban)	Low gravity (North Slope)	High gravity (Arabian Light)	Low gravity (Bachaquero)
Country of origin	**Nigeria**	**Nigeria**	**UAE**	**USA**	**S. Arabia**	**Venezuela**
Crude Oil						
Gravity	37.6	26.9	39.4	26.8	33.4	16.8
Sulphur (Wt.%) *	0.13	0.23	0.74	1.0	1.8	2.4
Sulphur Range (Wt.%)	0–0.5	0–0.5	0.51–1.0	0.51–1.0	1.0+	1.0+
Light End (<C4)						
Yield (Vol.%)	2.1	0.7	1.8	1.8	1.7	0.4
Light Naphtha (C5–100 °C)						
Yield (Vol.%)	6.4	2.1	6.7	5.8	9.0	2.5
Sulphur (Wt.%)	0.0002	0.001	0.012	0.01	0.024	0.01
Heavy Naphtha (100–200 °C)						
Yield (Vol.%)	22.0	8.7	21.2	12.6	8.4	6.0
Sulphur (Wt.%)	0.003	0.01	0.013	0.02	0.027	0.10
Kerosene (200–260 °C)						
Yield (Vol.%)	15.4	14.7	16.2	12.3	15.0	5.0
Sulphur (Wt.%)	0.03	0.063	0.058	0.2	0.094	0.48
Distillate (260–350 °C)						
Yield (Vol.%)	23.3	29.7	10.4	12.1	19.8	15.5
Sulphur (Wt.%)	0.13	0.18	0.47	0.56	1.05	0.99
Heavy Gas Oil						
Yield (Vol.%)	23.1	31.3	9.2	14.7	**	**
Sulphur (Wt.%)	0.21	0.31	1.06	0.9	**	**
Residual Fuel Oil						
Yield (Vol.%)	7.7	12.8	34.5	40.7	46.1	70.6
Sulphur (Wt.%)	0.39	0.48	1.49	1.74	3.08	3.01
TOTAL (%)	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

* Sulphur concentration units conversion: 1.0 Wt. % = 10,000ppm; 0.05 Wt.% = 500ppm ** Data for Heavy Gas Oil included in Residual Fuel Oil

Source: US Petroleum Refineries, National Petroleum Council (June 2000)

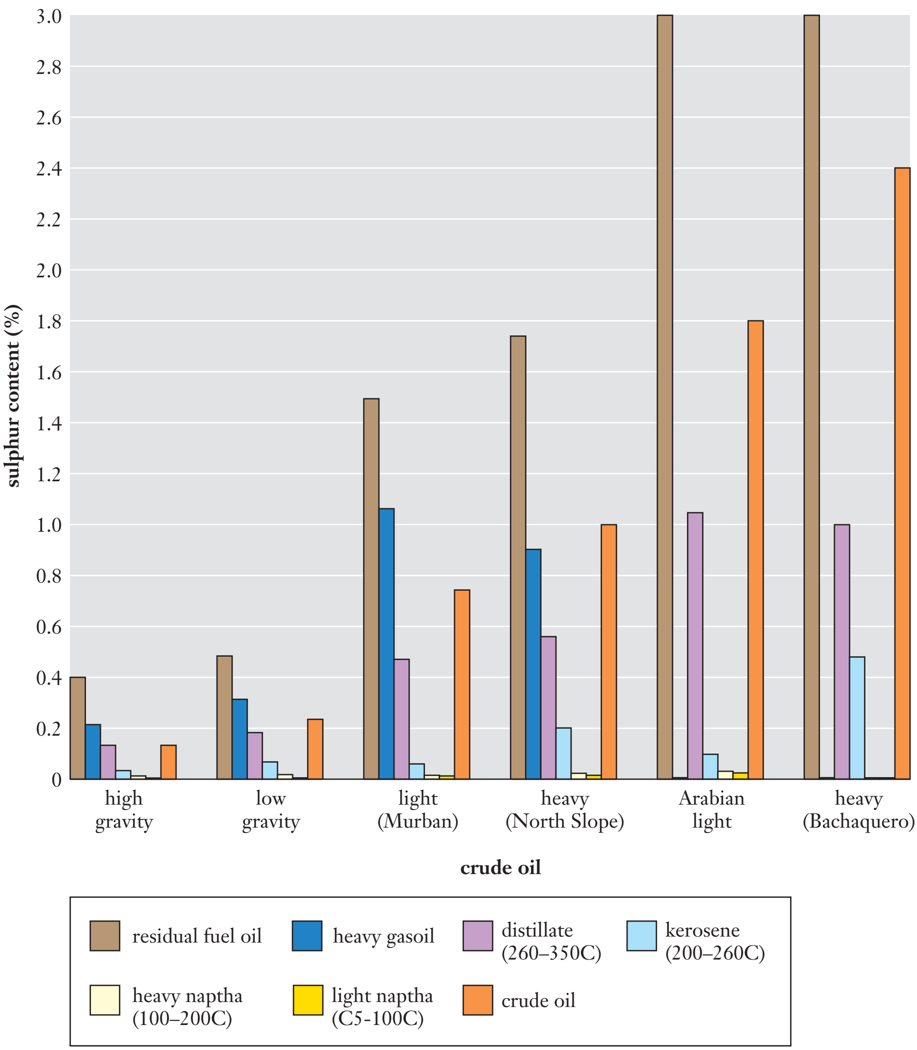
Figure C1: Typical products from a barrel of crude by region



product demand. It is immediately clear from Figure C1 that the USA is primarily a gasoline market, while other regions (for example Europe) produce higher proportions of 'middle distillates', i.e. kerosene, diesel and industrial gas oils.

Figure C2 depicts the observed distribution of sulphur in the various distillation fractions in a typical refinery, from various crude oils. The figure demonstrates how the sulphur concentration increases with the typical boiling point ranges of each of the distillation fractions. As such, light naphtha (<100 °C) has the lowest sulphur content, with increasing concentrations in heavier fractions, for example: heavy naphtha (100–200 °C), kerosene (200–260 °C), distillate (260–350 °C) and so on to residual fuel oil, which has the highest sulphur content.

Figure C2: Distribution of sulphur content (%) into different distillation fractions for some selected crude oils



Supplementary Document D:

Refining, sulphur removal and distribution basics

This document provides a brief description of the main refinery processes, with more detail on those that are essential for the removal of sulphur during the production of gasoline and diesel. Table D1 (overleaf) contains a compilation of the various types of refinery process units and auxiliary equipment that typify most modern complex refineries.

Fundamentals of petroleum refining operations

Petroleum refining operations have undergone tremendous increases in capacity and complexity since their inception in the 1800s. Equipment design has advanced greatly, product demand has shifted, specifications have become more stringent and feedstocks have changed with the changing nature of the sources of supply.

The first important step in the refining process is the distillation, first at atmospheric pressure, then under vacuum, which separates the crude oil into different fractions based on boiling point ranges. Historically, distillation was the only refining process employed. As the demand for products with different specifications has evolved so has refining technology, and a variety of process units were introduced downstream of the initial distillation step.

These downstream process units are classified into four primary groups:

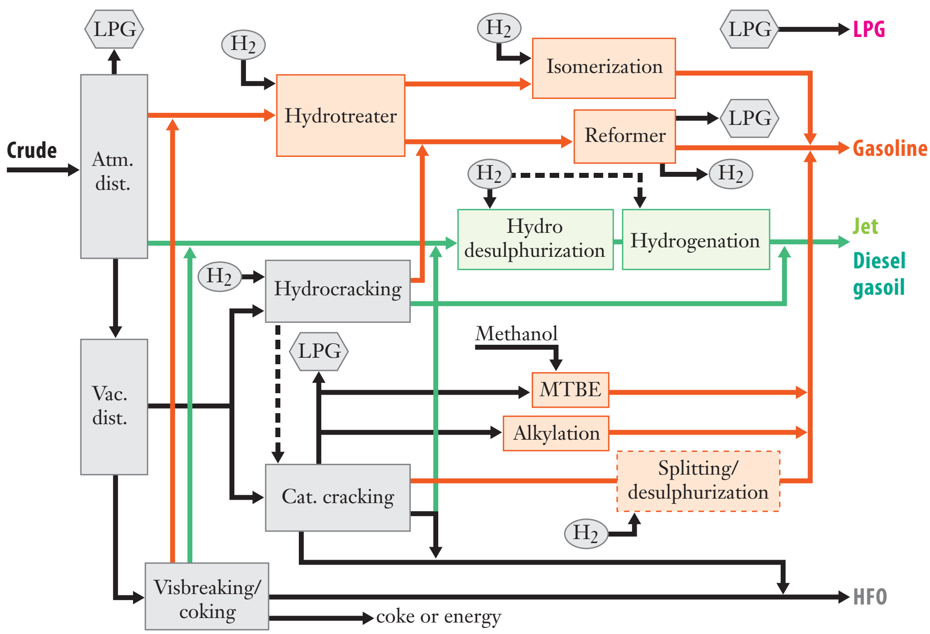
- **Cracking** of heavier distillate fractions into lighter ones, such as diesel and gasoline components.
- **Combining** lighter products such as iso-butane and butanes to make a high octane gasoline component.
- **Rearranging** the molecular structure to improve desirable qualities, such as reforming low-octane naphtha into high octane gasoline.
- **Treating**, to remove naturally occurring contaminants such as sulphur and nitrogen.

Figure D1 depicts schematically the layout and interconnection between refinery process units as found in many modern refineries (see Table D1). Comprehensive

Table D1: Descriptive listing of refinery process units

Process unit category	Typical units	Functional description
Separation of crude oil	• Atmospheric distillation • Vacuum distillation	Separate the crude oil fractions by boiling points
Breaking down heavy hydrocarbon molecules	• Catalytic cracking • Hydrocracking • Coking • Viscosity breaking • Thermal cracking	Change the size and structure of the hydrocarbon molecule. The conversion processes break heavier oil molecules into smaller, lighter, higher value products.
Combining hydrocarbon molecules	• Alkylation • Etherification • Polymerization	Combine small hydrocarbon molecules, typically gases, into larger, liquid oil products
Rearrangement of hydrocarbon molecules	• Catalytic reforming • Isomerizations	Rearrange the oil molecules to improve quality such as octane
Treating	• Hydrodesulphurization • Chemical treating	Remove naturally occurring contaminants such as sulphur, nitrogen and heavy metals
Blending hydrocarbon products	• Blending units	Blend hydrocarbon fractions or components produced by various refinery processes to obtain final products that meet local specifications
Auxiliary operating facilities	• Hydrogen production • Light-end recovery • Acid gas treating • Sour water stripping • Sulphur recovery • Tail gas treating • Wastewater treatment	Support the operation of the primary process units.
Refinery offsite facilities	• Storage tanks • Steam and power generation units • Flares • Blow down systems • Cooling water systems • Receiving and distribution systems • Fire control systems	Necessary equipment to support refinery operations. In addition, garages, maintenance shops, storehouses, laboratories and administrative buildings are also considered offsite facilities.

Figure D1: Schematics of the configuration of refineries with multiple process units



information about the fundamentals of refinery operations can be found in the US National Petroleum Council detailed description of the US Petroleum Refining Industry (NPC, 2000).

Technologies to reduce automotive fuel sulphur

The main technology used to reduce sulphur in gasoline and diesel is Hydrodesulphurization (HDS) or 'Hydrotreating', where hydrogen is added to react with sulphur compounds and convert the sulphur to hydrogen sulphide (H_2S). This is then removed and converted in a separate process to elemental sulphur. The hydrogen required may come from other parts of the refinery, but often a hydrogen manufacturing unit is needed. Many refineries already have HDS units to treat various refinery streams, but these are often low-pressure units with limited desulphurization capability. Modern HDS units operate at much higher pressures, and may be single-stage or two-stage depending on the level of desulphurization required. The descriptions in this section are intended merely as a quick overview of various options and do not represent an exhaustive list. No attempt is made here to quantify the costs of implementing these technologies, as these depend to a large extent on the existing refinery configurations.

Hydrotreating

Hydrodesulphurization (HDS) is a catalytic process that is used to remove sulphur, nitrogen and metal contaminants from petroleum liquids. The feedstock is mixed with hydrogen, then heated and fed to the catalyst reactor, where sulphur and nitrogen are converted into hydrogen sulphide (H_2S) and ammonia (NH_3) respectively. Product from the reactor goes to the high-pressure separators, where excess hydrogen is removed and returned to the reactor. The gases from the separator are sent to the gas treating system to remove H_2S.

Figure D2 presents a schematic outline of the process involved in the hydrotreating process.

Sulphur recovery unit

The sulphur recovery plant converts H_2S from the HDS units to elemental sulphur. The most widely used recovery system is the Claus process, which uses both thermal and catalytic conversion reactions. In the Claus process, some of the H_2S is burned to SO_2. The H_2S and SO_2 are then reacted to form sulphur and water. The sulphur can be typically sold for chemical or fertilizer production.

Tail gas treating unit

The Claus process typically recovers about 95% of the H_2S in the feed. The unrecovered H_2S exits the unit in the tail gas. The sulphur content of this tail gas may be above environmental, health and safety limits. Several processes are available to treat the tail gas from the Claus unit to further recover sulphur and reduce emissions. These include the 'Super Claus' (99% recovery), 'Claus Pol' and 'Sulfreen' (99.5% recovery), and Shell Claus Off-gas Treatment (SCOT) (99.9% recovery) processes.

Hydrogen manufacturing unit (HMU)

Hydrogen is required for a number of refining processes, including hydrotreating, hydrocracking and isomerization. The primary source of hydrogen in many refineries is the catalytic reforming process, which converts paraffins and naphthenes to aromatics. If this is not enough, especially when gasoline aromatic content is limited, additional hydrogen may be produced in an HMU by steam reforming of light hydrocarbons, primarily methane. The light hydrocarbons are mixed with steam and passed through catalyst filled tubes in the reformer furnace to form hydrogen and CO/CO_2. The reformer gas containing hydrogen, CO, CO_2 and excess steam is passed through a converter where CO and steam are further converted to hydrogen and CO_2. The CO_2-rich gas is treated with an alkaline stream to absorb CO_2, yielding 95–98% pure hydrogen with the balance being primarily methane.

Gasoline treatment options

The major source of sulphur in gasoline is from the catalytically cracked streams. The cat-cracked gasoline component can be split into two or three fractions, and it is these that must be desulphurized. and the loss of octane quality has to be replaced. There are a number of treatment technologies, described below.

- ***Conventional gasoline hydrotreating***
  This has been used in refineries for decades to reduce the sulphur content of hydrocarbon streams and is very well understood. Unfortunately this tends to convert olefins present in cat-cracked gasoline into lower-octane paraffins, causing an octane loss of as much as 10 numbers and high hydrogen consumption. This is undesirable since the low octane FCC gasoline is difficult to blend into the gasoline pool without further upgrading.

- ***Selective gasoline hydrotreating***
  New technologies allow conventional hydrotreating to achieve desulphurization without as much octane loss. Some of these processes use a modified catalyst under optimized conditions and add a step to regain octane lost in the hydrotreating reaction. Other processes are designed to increase reactions such as isomerization or aromatization. All of these selective hydrotreating processes limit octane loss but are usually accompanied by some loss in gasoline yield. Several such processes are currently commercially available, are in use in a number of EU refineries and will probably be used by some US refiners to produce blendstock for Tier 2 gasoline.

- ***Catalytic distillation***
  This technology has also been commercialized. Its basic premise is the use of hydrotreating catalysts within a distillation tower. The hydrotreating reaction is the same, but less hydrogen is used within the tower, which enables it to be more selective and minimize saturation of olefins.

- ***Adsorption***
  Two processes have emerged more recently that utilize adsorption technology to remove sulphur from the naphtha fraction. The Phillips process, S Zorb, has been demonstrated commercially; it utilizes an adsorbent that selectively adsorbs and reacts with sulphur molecules. The Black & Veatch process, IRVAD, is under development and utilizes another adsorbent that adsorbs sulphur molecules from the naphtha for further processing.

Diesel treatment options

Diesel fuel is made by blending various distillate fractions, all of which contain some sulphur. The ability to remove sulphur from diesel fuel depends primarily on the following parameters:

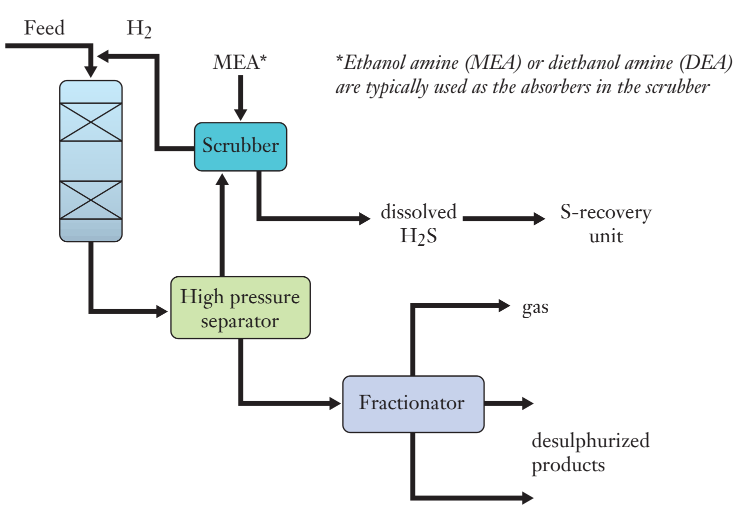
- the types of sulphur compounds in the crude;
- availability and operating pressure of existing hydrotreating units;
- availability of hydrogen and its purity; and
- the catalyst type used and its activity.

Untreated distillate blend-stocks may contain several thousand ppm of sulphur. The sulphur in these blend-stocks is commonly reduced by hydrotreating, which may require severe conditions (high-pressure and high temperature) to achieve very low sulphur levels. Depending on refinery configuration, some refiners might find it more advantageous to install a hydrocracker for production of greater amounts of lower sulphur diesel. Installation of new hydrocracking capacity is much more costly than that required for high temperature/high pressure hydrotreating. It has the advantage of producing more diesel fuel and kerosene, rather than the gasoline components produced by a cat-cracker.

While many refineries in the developing world are still producing high Sulphur diesel some are already contemplating various strategies to revamp their facilities and introduce new processing capacity to produce lower sulphur diesel. See Supplementary Document E: *Diesel treatment technologies* for a summary of a recent US study on diesel desulphurization.

- ***Hydrotreating*** *(refer to Figure D2)*
  Conventional hydrotreating works well for diesel fuel and can give some additional benefits including reduction in aromatics and a small increase in cetane quality. However, the degree of desulphurization available depends on the system design, capacity and especially operating pressure. Conventional low-medium pressure hydrotreaters work at 30 Bar and can reduce diesel sulphur levels to ≤1,000 ppm, depending on crude type. To make lower sulphur fuels from 500 down to 50 or 10 ppm S, more expensive high-pressure (50–70 bar) hydrotreaters are required, which may be single- or two-stage, depending on feedstock type and other requirements.

Figure D2: Schematics of typical refining hydrotreating process



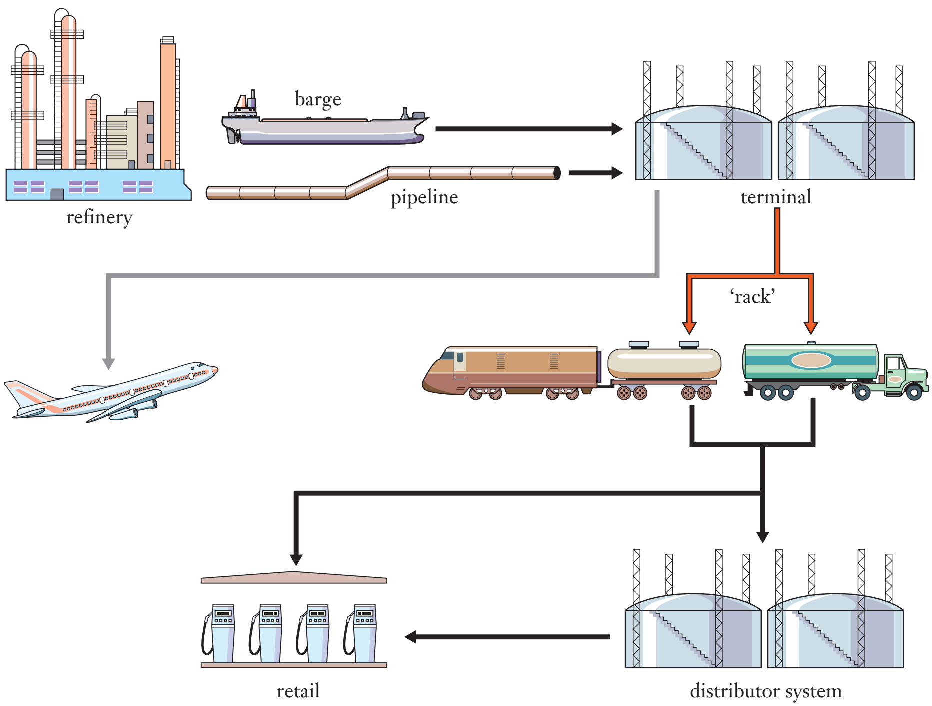
- ***Hydrocracking***
  This is an important yet expensive refinery processing technology that can used to increase the volume of low sulphur diesel and kerosene produced. Hydrocracking is an alternative to catalytic cracking (which makes mainly gasoline components); it produces high-value naphtha or distillate products from a wide range of refinery feedstocks. Hydrocracking can reduce sulphur levels in diesel to 50 ppm, however below this level, hydrotreating will still be required. Hydrocracking technologies have a long history of commercial application, with many tens (or even hundreds) of units of various sizes and operating conditions worldwide. Refiners who choose to install or revamp a hydrocracker must recognize that it is the most expensive option for producing lower sulphur fuels (about 4–5 times more expensive than a high-pressure hydrotreater). The main advantage of installing such a process unit is in its ability to upgrade heavy lower value products to diesel and kerosene. This will increase the yield of the diesel and kerosene fractions and will provide an economic return to the refinery.

Product distribution and logistics considerations for clean fuels

With very low sulphur fuels, contamination with higher sulphur products during distribution can be a problem. A typical fuel distribution system is illustrated in Figure D3. Although there can be variations in the distribution process, in the basic system fuel moves from the oil refinery in bulk shipment, by pipeline, ship or barge, to a terminal. A terminal is a storage and distribution facility. The terminal 'rack' refers to the mechanism used to dispense motor fuel products from the terminal into tank trucks or rail cars. From the terminal, the fuel typically goes to the wholesale distributor, sometimes to intermediate storage, then to the retailer and finally the consumer. Fuel may also go directly to the retailer from the terminal.

Many refineries have such loading facilities, or 'racks', that can deliver finished products directly onto trucks and railcars, although in many parts of the world refineries rely increasingly on pipelines and marine transportation for delivery of the majority of their production.

Figure D3: Schematics of fuel distribution and logistics network



Product transportation considerations

The movement of different product grades and batches from multiple shippers through a single pipeline requires careful control of how and when products are moved. Some of the batches shipped are 'fungible', namely they have the same product specifications and can be mixed during shipping. This will be the case of shipment of the same grade of gasoline, for example, from various refineries into a local distribution market.

Products that are sufficiently different from each other such that they should not be mixed are sent through the pipeline one after the other with no physical separation. A specific sequence is used to minimize the contamination of the adjacent product, though some mixing occurs at the interface between the batches. For example, an interface between regular and premium gasoline could be blended into regular gasoline. However, increasingly stringent product specifications, such as in the USA and Europe, are increasing the quality control requirements and could restrict the existing flexibility in the storage, handling and distribution of products.

For products transported by ship, barge, rail or truck, product integrity during movement is not a major issue provided the products are kept in separate sealed compartments. However, when ships or barges are loaded or offloaded there is a potential for generation of interface or 'transmix' in the same manner as discussed above for pipeline operation.

Product distribution considerations

When considering phasing down sulphur levels in fuels it should be noted that widening the differential between the highest and lowest sulphur products in the distribution system could increase the amount of 'transmix' and increase the operating costs and investments required.

General items to consider include:

- At lower sulphur levels, any significant (or even a small) amount of blending with other higher sulphur products will raise the final sulphur level above the specification. This will require a vigilant system of quality control and shipment of 'transmix' back to refineries for reprocessing.
- As the 'transmix' volume is expected to almost double when moving to low sulphur products, additional storage tanks will be required to store this 'transmix' along pipeline routes and at terminals pending its shipment back to refineries.
- Most points in the distribution system will need to have test equipment to check sulphur levels, with sufficient accuracy to determine sulphur at the required level.
- If the sulphur levels in gasoline and diesel are different, additional cost will be incurred due to the shipment interface of gasoline and diesel, which will also require additional processing back at the refinery.
- Different sulphur concentrations in different distillate products could also create cross contamination—for example, cross contamination in shipment and handling of high sulphur heating oil, jet fuel or non-road diesel, as compared to lower sulphur automotive diesel.

During local implementation of fuel sulphur strategies all these factors will need to be addressed. Careful planning and resources need to be devoted to upgrading the distribution and logistics system to avoid inadvertent cross-contamination as well as prevent product adulteration and ensure delivery of high quality products to the consumers.

Supplementary Document E:

Diesel treatment technologies

Summary of a recent US study on diesel desulphurization

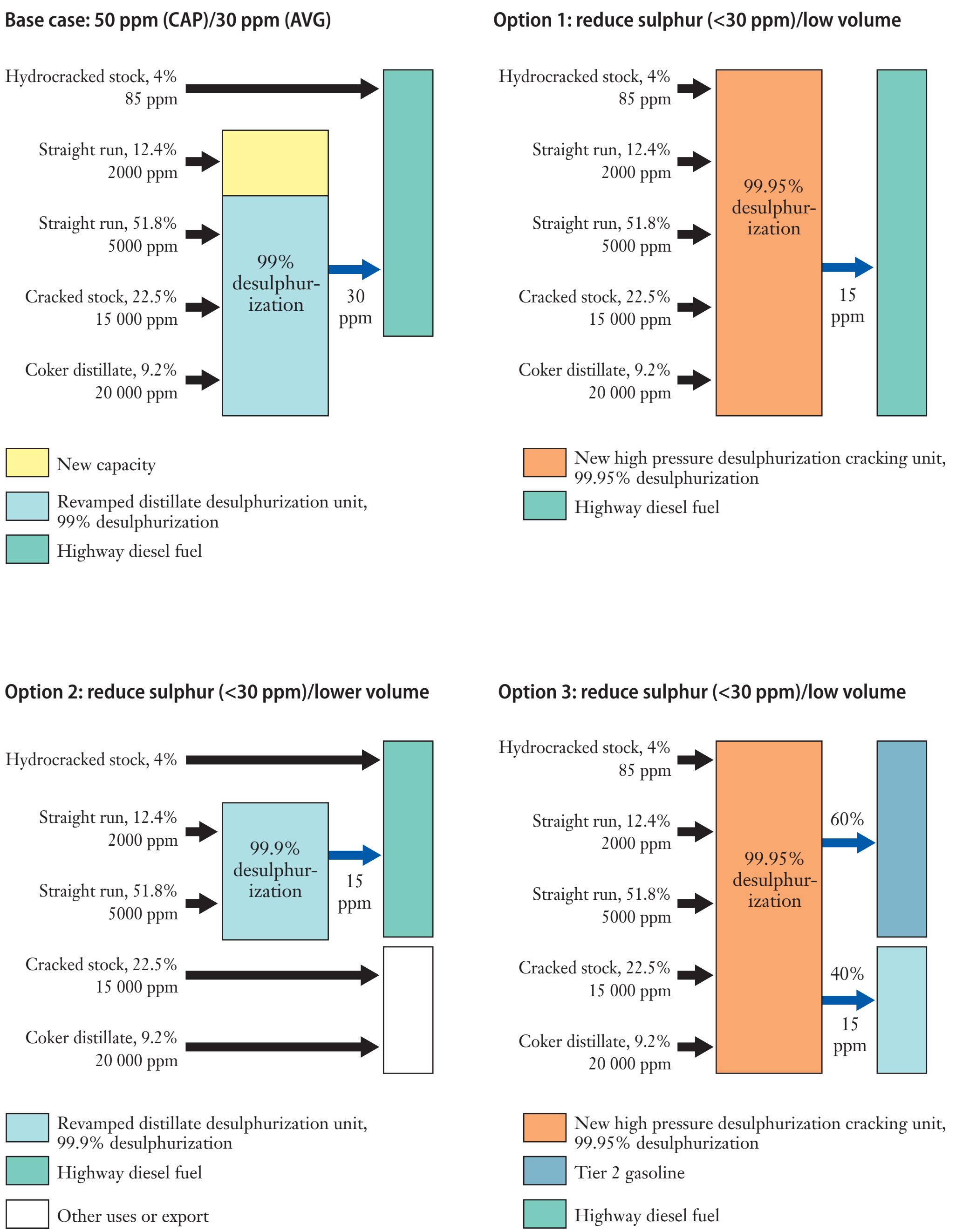
Figure E1 (overleaf) presents a set of specific examples for optional routes to the production of very low sulphur diesel, especially suited for those refiners that are contemplating producing diesel with 50ppm (or lower). Four different schematics are shown, marked 'Base Case' and Options 1, 2 and 3. These examples were constructed to show the range of options and their impact both on the resources required for revamping refineries and possible impacts on products yield.

The options presented are:

- **Base case**—assuming sulphur content with a cap of 50-ppm and a 30-ppm average. This will require reactor volumes and capacity with desulphurization units with at least 99% efficiency.
- **Option 1**—reducing sulphur content to < 30 ppm while maintaining automotive diesel volumes. This will be a very high cost option, at least 2–3 times more expensive than the base case. It requires the construction of high-pressure desulphurization cracking units with 99.95% treatment efficiency.
- **Option 2**—reducing sulphur content to < 30 ppm at a lower cost than option 1. This option will require constructing revamped distillate desulphurization units with 99.9% efficiency. Though this option is less costly it could result in about 30% loss of automotive diesel, as higher sulphur fractions that remain untreated are diverted to other products or exported.
- **Option 3**—reducing sulphur content to < 30 ppm and obtain a positive return on investment. This option will require almost as high a capital investment as in Option 1. It requires the construction of new high-pressure hydrocrackers with 99.95 % desulphurization efficiency. In order to get the needed return on investment this option will result in only 40% of the output being blended as automotive diesel while the remaining 60% used to blend US Tier 2 gasoline.

Continued …

Figure E1: Examples of options for producing lower sulphur automotive diesel



Source: API, EPA-EMA Meeting, 2000

Supplementary Document F:

Topics to be addressed when evaluating options for reducing fuel sulphur

Set up air quality policy goals

- Which pollutants?
- Which concentrations in air, and over what averaging time?
- Which population exposure, regional vs. local problem?

Evaluate emissions sources

- What is the contribution of transport emissions as compared to other emissions sources (stationary)?
- What is the issue with fuel sulphur relative to these emissions?
  - Direct emissions (SO_2)
  - Secondary effects (Sulphates, particulate matter)
  - Enabling advanced vehicle technologies

Consider local context for fuel sulphur reduction

- How will the contemplated measures impact the 'vehicle-fuel' system?
- What is the current range of sulphur in fuels?
  - **In the % range.** Direct air quality benefits could be attained from fuel changes with improved maintenance of current vehicle technology.
  - **Below 0.1 % (1000ppm).** Enables improved vehicle technology and delivers benefits only if such vehicle technologies are available.
- What is the cost-effectiveness of the various measured considered?
  - Avoid higher costs that will burden the economy without justification.
- Is the vehicle population equipped with appropriate technologies?
  - If not ready, introduction of lower sulphur fuels introduction can be completely counterproductive.

continued …

Assess fuel supplies and availability

- What are the local sources of the lower sulphur fuel products?
  - If local refineries provide all supplies, need to assess cost and time required for refinery modifications.
  - If all fuels is being imported, need to assess availability of secure sources for uninterrupted supplies.
- What are the necessary refinery modifications to produce lower sulphur fuels?
  - Switch to low-sulphur crude can reduce sulphur to ~0.1% only.
  - Increased energy demand and emissions for enhanced processing.
  - Capital expenditures for modifications and incremental cost of products.
- What are the needed changes to the fuels logistics infrastructure?
  - Expanded terminal capacity to hold various grades of fuels.
  - Need for new import terminals.
  - Contamination and adulteration of fuels during distribution.

Supplementary Document G:

The vehicle-fuel system: factors for consideration by policy makers

(a) **Vehicle use**—Level of vehicle use is important in the overall analysis of transportation emissions, particularly when seeking long-term solutions to help avoid the development of a problem. A central question for developing countries policy makers is whether avoiding growth in vehicle use is possible or desirable.

(b) **Vehicle fleet and technology used**—Older vehicles usually have higher emissions than newer vehicles, mainly due to performance deterioration and the use of obsolete, higher emitting technology. Emission limits for newer vehicles will ensure introduction of advanced emissions control technologies into the fleet. Specific measures to address emissions from in-use vehicles will also be important as it is expected that it will take a long time to turn over vehicle fleets, especially heavy-duty vehicles, in most countries.

(c) **Maintenance of vehicles**—Deterioration of emissions characteristics is linked to maintenance practices of owners, particularly where catalytic exhaust after-treatment technology is used. Misfuelling and neglect of exhaust after-treatment maintenance are likely to cause increased emissions, unless effective systems are put in place.

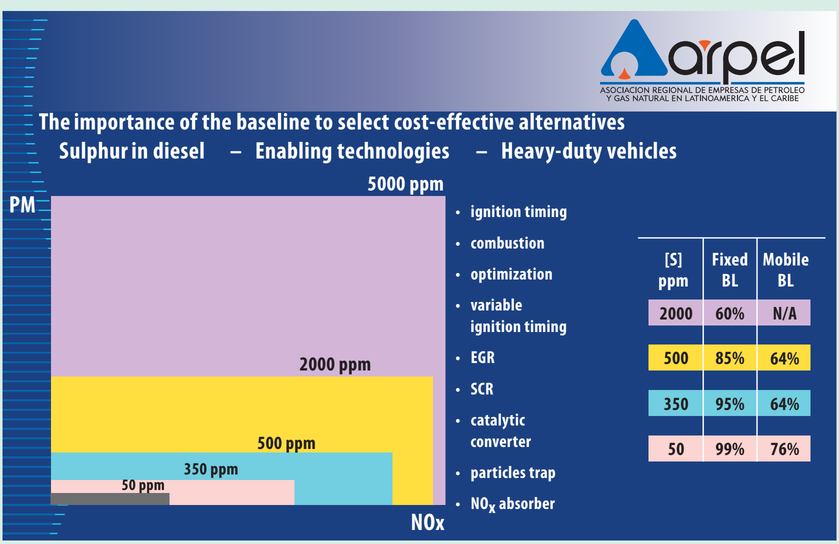
(d) **Use of appropriate fuels**—Regulatory authorities need to provide clear fuel specifications based on the vehicle technologies being introduced. In addition, steps are needed to prevent misfueling and eliminate unnecessary economic incentives to use the wrong fuels, thus prevent adulteration or illegal fuel substitution.

Supplementary Document H:

The importance of considering the starting baseline (or, beware of percentages!)

When discussing the impact of new technologies in terms of percent reductions it is important to state the starting baseline. To illustrate this concept we are using as an example developed by ARPEL, which demonstrates how the steps taken by OECD countries have allowed substantial reduction of PM and NO_x emissions from heavy-duty vehicles, while phasing-in lower fuel sulphur levels together with various vehicle technology options.

The Figure below exhibits the different vehicle technology steps with the appropriate diesel sulphur levels along with the PM and NO_x emissions reductions attainable by each step. The sizes of the colored rectangles in the figure are designed to depict the combined {PM + NO_x} emissions at each diesel sulphur level noted. The shrinking sizes of the rectangles show total emissions reductions achievable. Clearly the percentage emission reductions achieved in comparison with a 'fixed baseline' (e.g. a 5000-ppm sulphur level) are quite different than those that would be derived if we looked at a 'moving baseline', i.e. one that uses the previous level as its base.



If 5000 ppm sulphur is our starting point then going down to 2000 ppm sulphur could result in a 60% reduction of total {PM + NO_x} emissions, if the appropriate technological improvements noted to the right of the rectangles are implemented. As we step down to lower sulphur levels, and correspondingly lower emissions, we observe that further lowering sulphur levels to 500 ppm would amount to an overall 85% reduction (or an extra 25% from the previous level) in a 'fixed baseline' approach. Further reductions of sulphur levels to either 350 ppm or 50 ppm, will represent an overall 95% or 99% reductions, respectively, from the 'fixed baseline' (i.e. corresponding either 10% or 4% extra reductions from the previous level). However, if we use the 'moving baseline' approach, lowering fuel sulphur from 500 ppm to 350 ppm results can be described as a 64% reduction in total {PM + NO_x} emissions, and further reductions from 350 ppm to 50 ppm, would be indicated as an additional gain of 64%.

Therefore, in order to limit confusion, policy makers need to understand what is the starting baseline used for assessment of emission reduction scenarios and what is their associated cost-effectiveness under local circumstances. For developing countries, especially those starting with high levels of sulphur in their fuels, it is preferable to use the 'fixed baseline' approach as a tool that provides a better depiction of cost-effectiveness of each subsequent step in a phased approach.

Supplementary Document I:

Present and future investment in the refining business in Latin America and the Caribbean[1] (a case study)

Background

The ARPEL–OLADE–World Bank study[2] concluded that over the next decade the refining sector in Latin America and Caribbean (LAC) Region will require an on-going investment of about $3 billion a year (versus $2 billion for the previous decade) to meet demand growth and implement fuel quality improvement. Furthermore, increased usage of natural gas for power production and other stationary source application has diminished the market for heavy oils, therefore revamping refineries and introducing more conversion and upgrade technologies would be essential for their economic viability in the future.

Global trends continue to apply additional pressure on the industry to provide cleaner vehicle technologies' enabling fuels. The impact is on demand and quality. Moreover, issues such as the security of energy supply and environment, together with global, regional and local economic and political situations will also affect strategic corporate decision-making in the refining and fuel distribution sector in LAC.

This case study is based largely on the outcome of the workshop held during 30–31 March 2004 in Kingston, Jamaica, which was convened by ARPEL (Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean). The workshop aimed to address primarily the status and needs of upgrading of oil refineries in the LAC Region. Companies participating in the Workshop represent approximately 80% of the refining capacity of the Region. The refining sector is an

[1] Extracted from the ARPEL Report 'Present and Future of the refining Business in Latin America and the Caribbean' (2004)
http://domino.arpel.org/aplicaciones/biblioteca/ML_lib.nsf/1e0a5136509d7b4b03256caf006a2310/f35166635788481203256eb50061444a?OpenDocument (English version)
http://domino.arpel.org/aplicaciones/biblioteca/ML_lib.nsf/1e0a5136509d7b4b03256caf006a2310/6ec7b27eb9f9cf4503256f410062f3f2?OpenDocument (Spanish version)

[2] Refining Sector Development in Latin America and the Caribbean Study – 2002, ARPEL – OLADE – World Bank
http://domino.arpel.org/aplicaciones/biblioteca/ML_lib.nsf/1e0a5136509d7b4b03256caf006a2310/5964edb4b19dbc2903256cad00726ebe?OpenDocument

important part of the sustainable economic development of the Region. For this reason alone, this Workshop was important, and its conclusions are expected to form a part of future regional strategies.

The main issues addressed were:

- The need to upgrade facilities in order to increase operations efficiency and enhance profitability.
- Considerations of appropriate octane enhancers if MTBE is to be phased-out.
- Sharing both the successes and pitfalls of the Brazilian experience with Ethanol as a 'lessons-learned' for other refiners to consider.
- Resources needed to undertake the needed upgrades and funding options.

The workshop brought together 57 refining industry experts, government decision makers and funding agencies to share their perspectives on the issues. The discussion centered on experience and expectations resulting from emerging plans for optimization of process technologies while managing supplies, both for internal markets and for exports. It also focused on the need for cost-effective approaches to narrow the gap between existing funding resources and future investment needs.

Overview of discussion

Each of the participating companies addressed the following:

- General overview and current configuration of company in the Region;
- Investments made in the last 5–10 years;
- Plans related to the change in the product mix and fuels specifications;
- Funding sources planned;
- Lessons learned during the process.

The discussion on new refinery technologies centered on strategies that include:

- New catalysts;
- Process optimizations approaches including their direct and indirect impacts;
- Octane and cetane issues;
- Level of hydrogen production and consumption;
- Approaches to co-generation and their potential benefits; and
- Issues related to infrastructure upgrades.

In a number of countries in Latin America and the Caribbean, the government is the sole owner of their domestic refineries. These refineries are protected by means of import restrictions, quotas, subsidies, or high tariffs. This business structure has caused increased burden on governments due to their inability to attract capital for needed investment in the sector.

The discussion emphasized the need for sector restructure and reform. Various business models are being explored that will retain government control while opening up their markets to increased competition. Some of the approaches discussed range from various degrees of privatization, joint-venture models with publicly traded companies, licensing agreements for fuel manufacturing and distribution and others. It is clear that for countries where the downstream petroleum sector is not yet open, government decision makers will need to take a hard look at these issues if they want to be able to attract the investment that is needed to upgrade their facilities.

Table I1 provides a summary of the specific issues addressed and the discussion that ensued. One of the main findings in the discussion is that fuel specifications seem to be getting stricter than originally expected, as is shown in Figure I1. This trend is possibly linked to considerations of future viability of national companies in light of regional initiatives of market liberalization and the need to compete, possibly, in the near future in open markets. Furthermore, small refineries in the region are perceived as more viable than four years ago in light of reduced excess capacity and increased product demand.

Table I2 provides a glimpse of the projects and issues facing individual refineries in the LAC region in the next decade. The table also provides initial indication of estimated resources that would be needed in order to undertake all the envisioned refinery upgrades and improvements.

Conclusions and recommendations

All in all the participants felt that fossil fuels will continue to be the predominant energy source in the next 30 years. This is the context in which refiners need to consider demand needs as well as plan investments in potential expansion projects. The trend, for the LAC region in particular, is on processing increasingly heavier (and extra heavy) crude oils that create many technical problems and lead to gasoline and diesel yields. Participants also recognized the importance for industry to keep pace with market requirements of fuel quality

As refiners go through the change process, some considerations were viewed as vital to improved refinery management strategies:

- Integrating the areas of refining technology and production may support achieving a more cost-effective transition to stricter fuel specifications.
- Training and capacity building to develop multidisciplinary projects—required for upgrading/revamping of refineries—an important factor for success.
- Participating in benchmarking initiatives (e.g. Solomon's, etc.) as a means to improve business process efficiency.
- Assessing the indirect impacts of process changes when producing fuels with new specifications (e.g. what to do with the sulphur generated from severe desulphurization? Or what to do with petroleum coke if companies need to increase the usage of delayed coking processes?)

Notwithstanding everything that has already been accomplished, the issue of financing new projects for refinery configuration changes and fuel quality improvements is still a critical one. In order to facilitate and reduce the cost of financing such projects, changes are required in the context and modalities of the operation of state-owned companies in order to reduce the risks perceived by private investors. Such changes should include, most importantly,

I. Removing monopoly restrictions from the markets,
II. Allowing for free import and export of petroleum products, and
III. Establishing a relationship between international market prices and ex-refinery prices.

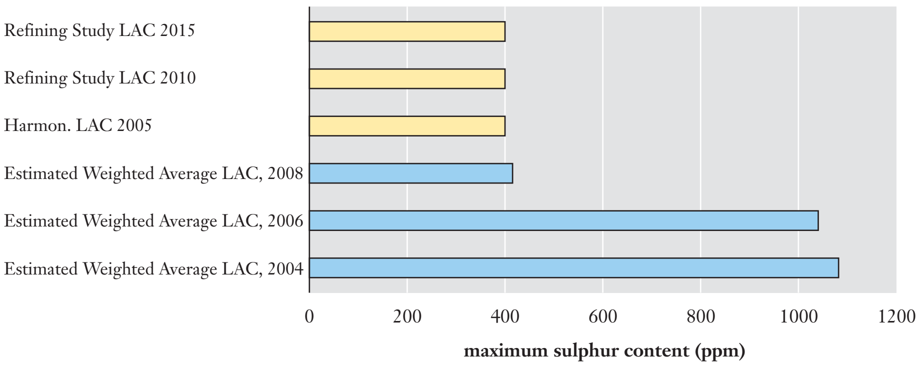
If these steps are taken, only the business case and not the regulatory framework will govern the perception of the risk by investors.

Table I1: Summary of issues and discussion

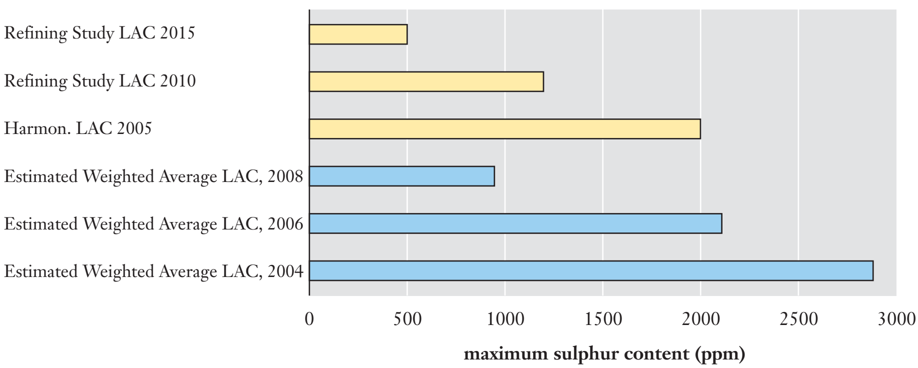
Issue addressed	Discussion summary
Why are fuel specifications in the LAC region getting stricter than originally expected?	• The main findings of the LAC Refinery Sector Development study are still applicable to the different countries in the region. • National fuel specifications are getting stricter due possibly to considerations of future viability of national companies. • Regional initiatives of market liberalization and the need to compete possibly in the future in open markets.
How should the LAC Region reconcile refining capacity and percent utilization (the latter without potential need for financing) to satisfy products' demand?	• The strategy could entail increasing utilization beyond 95% to take advantage of unused capacity in the short term. • Focus on investments in the medium and long term to optimize the use of available financing.
What are the consequences of the trend in the Region on processing increasingly heavier (and extra heavy) crude oils?	• This creates problems with acid corrosion, high viscosity and desalting. • Reduces gasoline/diesel yields. • Leads to higher energy intensity (and elevated GHG emissions) from such operations.
How should the LAC Region handle the increased utilization of ethanol?	• Concluded that up to a 10% ethanol content in gasoline does not seem to require retrofitting vehicles or to impose new environmental restrictions. • It could be used as an alternate octane enhancer (particularly in light of some initiatives to ban MTBE use in some countries). • Continue to monitor how this issue evolves at the country and regional level both in the LAC and the rest of North America.
Are small refineries still viable in the LAC region?	• Small refineries are perceived as more viable than four years ago, • They seem to have a niche role in serving markets with high transportation costs (island states). • They benefit from increased product demand, which is reducing excess capacity.

Figure I1: Sulphur content in fuels in the LAC Region

Maximum sulphur content in gasoline, LAC Region



Maximum sulphur content in diesel, LAC Region



Notes:

- Estimated Weighted Averages LAC {sulphur x (country consumption) / (total consumption)} – Calculated by ARPEL from maximum – present and proposed – regulated standards of major consuming countries of the Region. Sulphur concentration standards utilized for the calculation do not include the lower content enforced for larger cities (e.g. Buenos Aires, Santiago, Mexico City, etc.). Sulphur standards obtained from data available at the ARPEL Fuels Database (2004). Estimated consumption volumes extrapolated from data obtained from the World Bank (a.- 'The Demand for Oil Products in Developing Countries' - Discussion Paper No. 359 (1997) and b.- World Development Indicators web site)
- Harmon. LAC 2005 – Values derived from the study 'Harmonization of Fuels Specifications in Latin America and the Caribbean – 2005'
- Refining Study LAC 2010 and 2015 – Values utilized as a basis for the calculations included in the Study 'Refining Sector Development in Latin America and the Caribbean' (ARPEL – OLADE – World Bank, 2002)

Table I2: Snap shot of refiners plans for companies operating in the LAC region, and estimated capital expenditures for upgrades and modifications within the next decade[a]

Company	Refining capacity in the LAC region[b]	Countries in which it operates refineries	Steps taken to improve fuels quantity and quality	Resources needed
ExxonMobil	88.1 KBPD	Argentina	• Adequate distribution (potential for regional logistics) • Flexibility in the crude oil used • Optimizing yield • Additional hydrogen supply • Higher hydrotreating capacity • Additional sulphur recovery capacity	TBD
PDVSA	3.3 MMBD (worldwide capacity)	Venezuela and Caribbean (additional capacity also in the USA and Europe)	• Maximizing processing of crude and heavy crude oils and the conversion of residuals • Adapting operations for providing quality fuels • Optimizing the crude/product ratio • Improving products management (e.g., segregating crude oils, products and intermediate streams) • Developing low sulphur gasoline/diesel and other products such as asphalts, lubricants and waxes	US$ 5 billion in the next 5 years. (Of these, almost 16% will be to address fuel quality).
PEMEX	1.68 MMBD	Mexico	• Improving crude oil conversion processes • Use of residuals to co-generate electricity and steam • Processing of heavy crude oil' • Increase the commercialization of oil products • Maximize the use of the presently available refining capacity	TBD

continued . . .

Table I2: Snap shot of refiners plans for companies operating in the LAC region, and estimated capital expenditures for upgrades and modifications within the next decade[a]

Company	Refining capacity in the LAC region[b]	Countries in which it operates refineries	Steps taken to improve fuels quantity and quality	Resources needed
PETROBRAS	2.084 MMBPD	Brazil, Argentina and Bolivia	• Address increasing reliance on —heavier- Brazilian crude • Optimize operations and technology for higher acidity, viscosity and corrosion • Residue conversion to address demand for fuel oil, gasoline and diesel	US$ 5.5 billion in the next 5 years (1/3 to increase refinery conversion, 1/3 for gasoline & diesel fuel quality, and the rest for EHS, automation, and maintenance)
Repsol YPF	482.5KBPD	Argentina and Peru (additional capacity also in Spain)	• Adapting stricter fuels specs • Need for more middle distillates and less gasoline and fuel oil • Address fuel quality and conversion in a joint strategy involving FCC naphtha fractioning, desulphurization, hydrogen generation, and sulphur recovery • Addressing costs reduction and management systems improvement, including environmental safety and quality aspects	TBD
ANCAP	50 KBPD	Uruguay	• Installed new naphtha hydrotreater, a continuous regenerating reformer, and an isomerization unit • Processes installed provide sufficient hydrogen to allow for limited hydrotreating • Revamped the refinery with utilities and other offsite modifications	US$ 131 million in recently completed expansion and upgrade

Table I2: Snap shot of refiners plans for companies operating in the LAC region, and estimated capital expenditures for upgrades and modifications within the next decade[a]

Company	Refining capacity in the LAC region[b]	Countries in which it operates refineries	Steps taken to improve fuels quantity and quality	Resources needed
ECOPETROL	277 KBPD	Colombia	• Increased fuel oil production in vacuum units • Production of international quality asphalt • Inventories optimization • Implementation of risk-based management system • Implementation of flare loss reduction and optimization of steam distribution	US$ 155 million over a 6 years period (started in 2001)
ENAP	226.5 KBPD	Chile	• Installing process units for benzene saturation, mild hydrocracking of diesel, depentanizing of cracking gasoline and hydrotreating	US$ 319 million over a 6 year period (started in 2001)
PETROJAM	34 KBPD	Jamaica	• Change production technology from hydroskimming to conversion • Focus in short term on operating efficiencies and cost savings	TBD
PETROECUADOR	165 KBPD	Ecuador	• Desulphurization units for FCC and visbreaking gasoline • Increased gas oil production • Increase FCC gasoline production • Increase the efficiency of visbreaking units • Install high conversion units, • Design and build a new 100 KBPD refinery	US$ 1.7 billion

continued . . .

Table I2: Snap shot of refiners plans for companies operating in the LAC region, and estimated capital expenditures for upgrades and modifications within the next decade[a]

Company	Refining capacity in the LAC region[b]	Countries in which it operates refineries	Steps taken to improve fuels quantity and quality	Resources needed
RECOPE	25 KBPD	Costa Rica	• Expansion of the capacity of the vacuum distillation unit, kerosene hydrotreatment, catalytic reforming, and diesel hydrotreating • Conversion of a catalytic reformer into a light naphtha isomerization • Enhance processes to comply with the refinery and products' environmental standards	US$ 116 million
STAATSOLIE	7.3 KBPD	Suriname	• Raise throughput to 15 KBPD by install a new vacuum distillation and thermal visbreaking unit, an HVGO hydrotreatment unit (including hydrogen and sulphur unit) and a 30 MW modular expandable HFO power plant • Environ considerations include the construction of a wastewater treatment unit, a biological phenol treatment plant, and an LVGO caustic treatment unit including a spent caustic module	US$ 180 million

[a] Based on information from the ARPEL workshop report [ARPEL, 2004].

[b] Refinery Capacity: KBPD = 1,000 barrels per day of crude oil, MMBPD = 1 million barrels per day of crude oil.

‘Fuel sulphur’ on CD-ROM

This document is included on the attached CD-ROM in PDF format†. The file includes links to other files on the CD-ROM and to resources on the Internet*. The links are represented in this printed version by the blue underlined text.

†Requires Acrobat Reader™ *Web browser and Internet connection required

The International Petroleum Industry Environmental Conservation Association (IPIECA) was founded in 1974 following the establishment of the United Nations Environment Programme (UNEP). IPIECA provides one of the industry's principal channels of communication with the United Nations.

IPIECA is the single global association representing both the upstream and downstream oil and gas industry on key global environmental and social issues. IPIECA's programme takes full account of international developments in these issues, serving as a forum for discussion and cooperation involving industry and international organizations.

IPIECA's aims are to develop and promote scientifically-sound, cost-effective, practical, socially and economically acceptable solutions to global environmental and social issues pertaining to the oil and gas industry. IPIECA is not a lobbying organization, but provides a forum for encouraging continuous improvement of industry performance.

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