Final Consultants' Report

A Road Map for Cleaner Fuels and Vehicles in Asia

TA 6144 (REG): Better Air Quality Management in Asia

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ABBREVIATIONS

ACEA	–	Association des Constructeurs Européens d'Automobiles (European Automobile Manufacturers Association)
ADB	–	Asian Development Bank
AMEICC	–	ASEAN Economic Ministers and Minister of Economy, Trade and Industry of Japan Economic and Industrial Cooperation Committee
ASEAN	–	Association of Southeast Asian Nations
B	–	baht (Thailand)
CAI-Asia	–	Clean Air Initiative for Asian Cities
CARB	–	California Air Resources Board
CNG	–	compressed natural gas
CNY	–	yuan (People's Republic of China)
CO	–	carbon monoxide
CO_2	–	carbon dioxide
DOC	–	diesel oxidation catalyst
ECU	–	European currency unit
EGR	–	exhaust gas recirculation
EN	–	European Standard (set by the European Committee for Standardization)
EPEFE	–	European Programmes on Emissions, Fuels and Engine Technologies
ETBE	–	ethyl tertiary-butyl ether
EU	–	European Union
FCC	–	fuel catalytic cracking
HC	–	Hydrocarbon
HK$	–	Hong Kong, China dollar
IEA	–	International Energy Agency
IQ	–	intelligence quotient
JAMA	–	Japan Automobile Manufacturers Association
JCAP	–	Japan Clean Air Program
£	–	pound sterling (United Kingdom)
Lao PDR	–	Lao People's Democratic Republic
LPG	–	liquefied petroleum gas
LSD	–	low sulfur diesel
MMT	–	methylcyclopentadienyl manganese tricarbonyl
MTBE	–	methyl tertiary-butyl ether
NO_X	–	nitrogen oxides
NO_2	–	nitrogen dioxide
OBD	–	on-board diagnostic
OECD	–	Organisation for Economic Co-operation and Development
OMV	–	open market value
P	–	peso (the Philippines)
PAH	–	polycyclic aromatic hydrocarbons
Pb	–	Lead
PRC	–	People's Republic of China
PM	–	particulate matter
PM_{10} ($PM_{2.5}$)	–	particulate matter with diameter less than or equal to 10 (or 2.5) microns

PERTAMINA	–	Perusahaan Tambang Minyak Nasional (National Oil Mining Company)
RFG	–	reformulated gasoline
RM	–	ringgit (Malaysia)
Rp	–	rupiah (Indonesia)
RVP	–	Reid vapor pressure
S	–	sulfur
S$	–	Singapore dollar
SCR	–	selective catalytic reduction
SO_2	–	sulfur dioxide
SO_3	–	sulfur trioxide
TAME	–	tertiary-amyl methyl ether
TEL	–	tetraethyl lead
TERI	–	The Energy and Resources Institute
Tk	–	taka (Bangladesh)
TML	–	tetramethyl lead
TSP	–	total suspended particulate
UK	–	United Kingdom
ULSD	–	ultra low sulfur diesel
US	–	United States of America
US$	–	United States dollar
US EPA	–	United States Environmental Protection Agency
W	–	won (the Republic of Korea)
WHO	–	World Health Organization
¥	–	yen (Japan)

WEIGHTS AND MEASURES

bbl (barrel)	–	159 liters of oil
°C	–	degrees Celsius
E10	–	gasoline blend containing 10% ethanol by volume
E85	–	gasoline blend containing 85% ethanol by volume
E100 (or E150)	–	percentage of gasoline distilled at 100°C (or 150°C)
g	–	Grams
kg	–	Kilograms
kPa (kilopascal)	–	1,000 pascals
m^3	–	cubic meter
MBBLS/SD (million barrels per stream day)	–	a unit of oil refining capacity within 24-hours of continuous operation
µg (microgram)	–	0.000001 grams
mg/l	–	milligrams per liter
Pa (pascal)	–	1 newton per square meter, a unit of pressure
ppb	–	parts per billion, a unit of concentration
ppm	–	parts per million, a unit of concentration
T50, T90, orT95	–	temperature at which 50%, 90%, or 95%, respectively, of fuel distills
vol % (percent volume)	–	a unit of concentration
wt % (percent weight)	–	a unit of concentration

GLOSSARY

1,3-butadiene: An air toxic emitted during fuel combustion.

Alkane: Hydrocarbons linked together exclusively by single bonds; also known as paraffins. Hydrocarbon emissions are one of the main air pollutants regulated by vehicle emission standards.

Alkylation: Process in which light, gaseous hydrocarbons are combined to produce high-octane components of gasoline.

Aromatics: Hydrocarbon fuel molecules containing at least one benzene ring. Principal aromatics include benzene, toluene, ethylbenzene, and xylene, and are one of the heaviest fractions in gasoline.

Benzene: A known carcinogen, benzene is an aromatic compound that occurs naturally in gasoline and a product of catalytic reforming used to boost octane levels. Air emissions of benzene are specifically regulated in some vehicle emission standards.

Cetane number: A measure of auto-ignition quality that depends on fuel composition and relates to the delay between fuel injection into the cylinder and ignition.

Complex refineries: Large facilities that have a wide range of processing capabilities beyond those of topping and hydroskimming refineries to alter product yields and quality, including the capacity to crack fuels.

Diesel fuel: Complex mixture of hydrocarbons, consisting primarily of paraffins, napthenes, and aromatics, with organic sulfur present, used as a fuel in internal combustion engines.

Diesel particulate filter: Device used to reduce the total number of particles emitted from the combustion of fuel.

Distillation: Boiling range of fuel.

Ethanol: A high-octane oxygenate currently produced from renewable sources such as corn or sugar crops.

Ethyl tertiary-butyl ether (ETBE): Fuel oxygenate produced by processing ethanol with isobutylene, usually made from natural gas.

Euro: Shorthand reference for European emission standards. For light-duty vehicles, the phases of the standards as implemented over time are referred to as Euro 1, Euro 2, etc.

Ferrocene (dicyclopentadienyl iron): Coordination compound of iron and two molecules of cyclopentadiene that may be added to gasoline to prevent engine knock, and to diesel fuel to facilitate trap regeneration.

Gasoline: Complex mixture of volatile hydrocarbons used as a fuel in internal combustion engines.

Hydrocarbons: Simplest organic compounds, consisting only of hydrogen and carbon atoms.

Hydroskimming refineries: Typically mid-sized facilities that, in addition to distillation processes, include processes for catalytic reforming of some of the distillation streams. May include hydrotreating or hydrofinishing processes to improve the quality of the various distillation fractions produced.

Isomerization: Process in some complex petroleum refining that converts certain molecules into more complex molecules of substantially higher octane number.

Lead: Additive blended with gasoline during the refining process primarily to boost octane levels. May be either tetraethyl lead (TEL) or tetramethyl lead (TML).

Lubricity: Measure in the reduction in friction of a lubricant.

Methanol: Produced mainly from natural gas and used for the production of methyl tertiary-butyl ether (MTBE) and formaldehyde. Properties include a very high octane value, high affinity to water, and high corrosiveness.

Methyl tertiary-butyl ether (MTBE): Fuel oxygenate once widely used because of its combination of high octane value, compatibility with gasoline and fuel system components, favorable effects on fuel properties (i.e., effects on distillation and dilution), and supply availability.

Methylcyclopentadienyl manganese tricarbonyl (MMT): Manganese-based compound marketed as an octane-enhancing fuel additive for gasoline and as a possible additive for reducing smoke in diesel fuel. The manufacturer, Afton Chemical Corporation, holds a registered trademark in mmt® Fuel Additive.

Nitrogen oxides (NO_X): One of the primary air pollutants of concern from the combustion of fossil fuels.

NO_X adsorber: Device used to reduce NO_X emissions from a lean burn internal combustion engine. Also known as a NO_X storage catalyst or lean NO_X trap.

Octane rating: Measure of a fuel's ability in an internal-combustion engine to resist premature detonation, otherwise known as "auto ignition," "pinging," or "knock."

Olefins : Hydrocarbon compounds involved in the petroleum refining process, also known as alkenes, that contain at least one double bond.

Oxygenates: Chemicals containing oxygen that are added to fuels, especially gasoline, to make them burn more efficiently.

Paraffins: Alkanes (hydrocarbons with only single bonds).

Particulate matter (PM): A common air pollutant associated with combustion of fuels. Measured and regulated based on different sizes: Total suspended particulate (TSP); PM that is 10 microns or less in diameter (PM_{10}); and PM that is 2.5 microns or less in diameter ($PM_{2.5}$).

Pharmacokinetics: Study of how chemical concentrations change and move in the body over time.

Polycyclic aromatic hydrocarbons (PAH): Heavy organic compounds found mostly in diesel PM but which can also be present in the gas phase. Also known as polynuclear aromatic hydrocarbons and polyaromatic hydrocarbons.

Polymerization: Process of converting light olefin gases including ethylene, propylene, and butylene into hydrocarbons of higher molecular weight and higher octane number that can be used as gasoline blending stocks.

Reid vapor pressure (RVP): A measure of the volatility of gasoline in kPa at 37.8°C. Largely determined by the fuel's butane content.

Selective catalytic reduction: Means of converting NO_X with the aid of a catalyst into diatomic nitrogen and water.

Soluble organic fraction: Organic proportion of diesel particulates.

Sulfur (or sulphur): Abundant multivalent nonmetal that occurs naturally in crude oil.

Tertiary-amyl methyl ether (TAME): Fuel oxygenate produced by a process similar to that for ETBE, but from methanol and isoamylenes.

Topping refineries: Typically small facilities that rely exclusively on crude oil distillation for the production of various distillate components that receive very little processing. Residuum from the distillation process is sold as fuel oil, converted to asphalt, or sold to other refineries with additional processing capability.

Vapor lock: Occurs when too much vapor forms in the fuel lines and fuel flow to the engine decreases, resulting in loss of power and rough engine operation or engine stalls.

Viscosity: Indicates a fluid's resistance to flow—the higher the viscosity, the greater the resistance.

ACKNOWLEDGMENTS

Reducing vehicle emissions has been an important concern of the Clean Air Initiative for Asian Cities (CAI-Asia) since its establishment in 2001. CAI-Asia has actively campaigned for the improvement of fuel quality, an essential step in reducing vehicle emissions, which contribute significantly to air pollution in all of Asia's cities.

This report, *A Road Map for Cleaner Fuels and Vehicles in Asia*, is the outcome of a long process that began with a meeting in July 2003 in Singapore, where 12 major regional and national oil companies gave their recommendations to CAI-Asia on how to approach the formulation of a road map for cleaner fuels and vehicles in Asia.

CAI-Asia took the lead to compose this report, which was prepared by a team of specialists consisting of Grant Boyle, John Courtis, Cornie Huizenga, John Rogers, and Michael Walsh. Herbert Fabian provided valuable assistance in data collection and outreach activities on the report. Aurora Fe Ables, Agatha Diaz, and Gianina Panopio assisted in references validation and report formatting.

A draft of this report was presented at a regional workshop in May 2006 in Mandaluyong City, Metro Manila, Philippines. The comments received from participants in this workshop were especially useful in revision of the text and preparation of the final report.

Special thanks are due to the staffs of the Health Effects Institute, Shell, and the United States Environmental Protection Agency (US EPA) who carefully reviewed the relevant sections of this report and provided extensive comments and inputs.

CAI-Asia also benefited greatly from the discussions and comments received in the numerous workshops, conferences, and meetings on fuels and vehicles, to which CAI-Asia was invited to participate and present the road map as it was being formulated.

The Asian Development Bank, through a technical assistance grant, financed the development of this report. In their capacity as project officers, David McCauley, Charles Melhuish, Daniele Ponzi, and Masami Tsuji facilitated CAI-Asia's preparation of this report.

This report is dedicated to the memory of Kong Ha, the late Chairperson of CAI-Asia. Kong was passionate about reducing emissions from the transport sector, and he was passionate about this report. The implementation of its recommendations will be a lasting tribute to Kong Ha and will help the people of Asia breathe cleaner air.

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EXECUTIVE SUMMARY

Air pollution continues to pose a significant threat to the environment and the health and quality of life of Asia's urban population. The World Health Organization (WHO) has estimated that more than 530,000 premature deaths in Asia are due to urban air pollution. Motor vehicles, including passenger cars, motorcycles, scooters, and heavy-duty buses and trucks, are almost always a major source of this air pollution in Asian cities. Key emissions from motor vehicles include carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_X), and volatile organic compounds including unburned hydrocarbons (HC). Emissions of these pollutants depend a great deal on the quality of the fuels used, the engine technology, and the emission control devices used on vehicles.

Vehicle emissions in many Asian countries are expected to increase over the next few decades, as the vehicle population increases. If no action is taken to clean up fuels and vehicles, urban air quality will continue to decline. Reducing emissions from motor vehicles depends upon introducing cleaner fuels for the advanced emission control technologies that require these cleaner fuels. A key first step has been the worldwide drive to eliminate lead in gasoline, which has resulted in more than 90% of the world's gasoline becoming lead-free. It is now time to address all fuel issues, including sulfur in fuel, additives, and other fuel components.

A Road Map for Cleaner Fuels and Vehicles in Asia is designed to provide decision makers with up-to-date information on how to clean up fuels in Asia by developing their own road maps. This regional road map discusses the interaction between fuels and vehicle technologies and the approaches that Asian refineries can take to produce cleaner fuels, and it recommends next steps. The following are among the key conclusions drawn from extensive study.

(i) **Clean fuels are essential**. Pollution control experts worldwide have come to realize over the past 30 years that cleaner fuels are a critical component of an effective clean air strategy. In recent years, this understanding of the critical role of fuels deepened and spread to most regions of the world. Fuel quality is now seen as not only essential for directly eliminating or reducing pollutants such as lead, but also as a precondition for introducing many important pollution control technologies (e.g., the lowering of sulfur content to enable use of diesel particulate filters). Further, one critical advantage of cleaner fuels has emerged—its rapid impact on both new and existing vehicles. For example, tighter new vehicle standards can take 10 or more years to be fully effective, but the removal of lead in gasoline in Asia has reduced lead emissions from all vehicles immediately.

(ii) **A systems approach is essential.** Fuels and vehicles are parts of an integrated system and must be addressed together. The main benefits of reducing emissions will be realized through the coupling of cleaner fuels with advanced emission control devices.

(iii) **Fuel quality and vehicle emission standards should be regulated together.** Because most Asian countries have adopted European vehicle (Euro) emission standards, European fuel parameters are an important reference point, especially as the fuel quality and emission standards in Europe represent an integrated approach to reducing air pollution from the transportation sector.

(iv) **Reducing sulfur is essential.** Once lead has been removed, sulfur levels in both gasoline and diesel fuels are the primary fuel parameter to be addressed in developing a country's fuel road map. Reducing sulfur in fuels is a key measure in reducing air pollution from motor vehicles. High sulfur levels reduce the effectiveness of advanced three-way catalysts for gasoline vehicles and clog particulate filters in diesel vehicles. Almost all Asian countries will be adopting increasingly stricter Euro emission standards, which require reduced sulfur fuels, with an ultimate goal of 50 ppm or less sulfur in diesel and gasoline.

(v) **The benefits of reducing sulfur are clear**. Extensive studies in both developed and developing countries, including the United States (US), Mexico, and the People's Republic of China (PRC), have estimated that the economic benefits of an integrated system of clean fuels and vehicles far outweigh the costs. The estimated benefit cost ratios of these programs are 15:1 in the United States, and 20:1 in the PRC.

(vi) **Cleaner fuels are cost-effective**. The incremental costs of meeting the recommended level of fuel sulfur in Asia average 0.2–0.8 US cents per liter for gasoline and 0.5–0.8 US cents per liter for diesel. Further reductions to 10 ppm or below would add about 0.6 US cents per liter to the cost of diesel fuel.

(vii) **Current refinery expansion creates a window of opportunity**. The increasing demand for transportation fuels in Asia is resulting in the construction of new refineries, and the upgrading or expanding of existing refineries in the region, thereby creating a window of opportunity to produce the clean fuels necessary for reducing emissions.

(viii) **There are no technical obstacles to produce cleaner fuels in Asia.** The refining technology needed to produce cleaner fuels that meet Euro 4 or equivalent standards is well understood and has been successfully implemented in the United States and Europe.

(ix) **Enhancing octane requires careful consideration.** Prominent health experts have raised serious concerns regarding the potential adverse health effects of metallic additives such as methylcyclopentadienyl manganese tricarbonyl (MMT) and ferrocene, along with their potential adverse impacts on vehicle emissions and emission control system components. Therefore, the environmentally responsible approach for Asian countries is to apply the precautionary principle for these metallic additives and to not use them until and unless the scientific and health studies show that they are safe. Other additives, such as ethanol, methyl tertiary-butyl ether (MTBE), ethyl tertiary-butyl ether (ETBE), and tertiary-amyl methyl ether (TAME), have not been shown to cause significant health effects. Longer-term solutions applied by many refineries to meet the gasoline octane requirements are capital investments in enhanced refining capacity and blend-stock selection, and the use of certain oxygenates.

(x) **Taxing policy and other incentives are effective.** Experience worldwide indicates that governments can accelerate the introduction of cleaner fuels and their uptake in the fuels market through a balanced and thoughtful combination of tax and pricing policies.

(xi) **Fuel adulteration must be prevented.** Whatever fuel specifications are adopted in Asia, it is important to have routine monitoring at the pump and along the distribution chain to ensure that the actual fuels in the marketplace meet the required specifications. Penalties should be imposed if limits are not achieved.

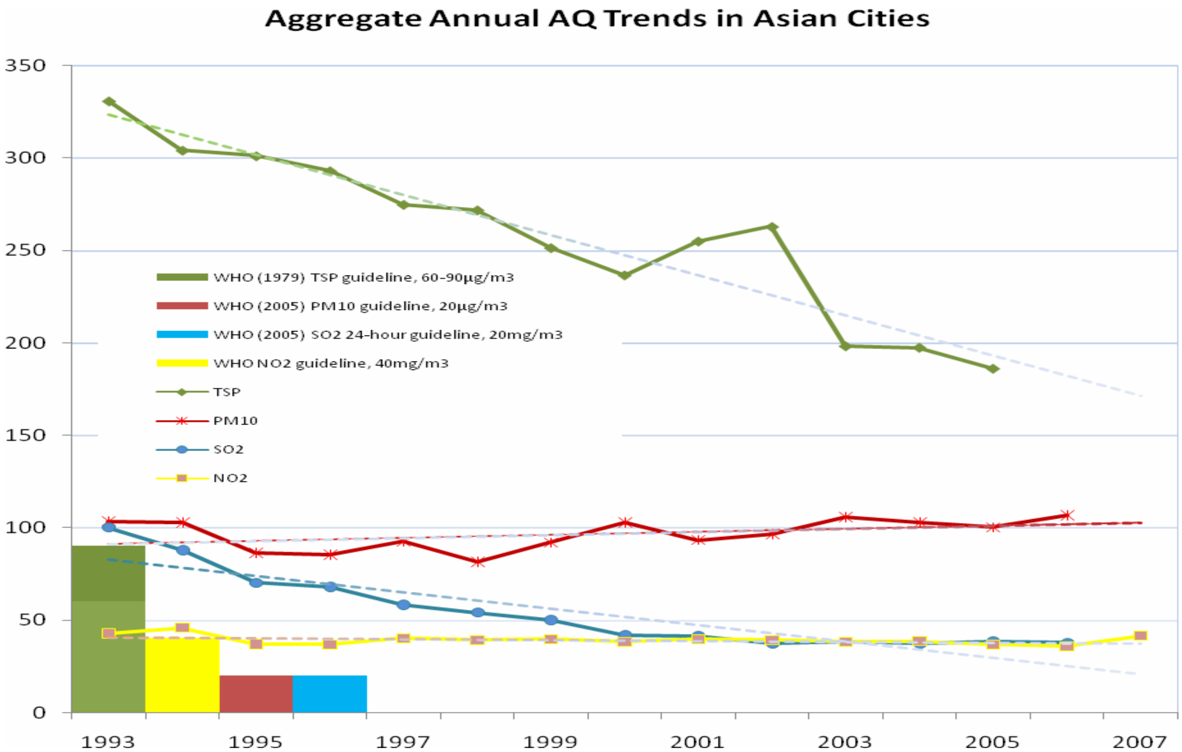
(xii) **All stakeholders should be involved in making decisions.** Decisions on the introduction of cleaner fuels should include a dialogue among all stakeholders, including environmental and public health officials, the oil refining sector, vehicle and engine manufacturers, and ministries concerned with oil pricing and taxation.

(xiii) **It is important to raise awareness about air pollution and vehicle emissions.** Intensified awareness-raising at the national and subnational levels is important for making the priority of cleaner fuels understood. Efforts in this regard should focus on both decision makers and the general public.

I. INTRODUCTION

1. Air pollution continues to pose a significant threat to the environment and quality of life and health of Asia's urban population. A study by the Clean Air Initiative for Asian Cities (CAI-Asia), summarizing air quality data from 20 cities[1] in Asia for from 1993 to 2005 showed that on average, pollution levels for sulfur dioxide (SO_2), total suspended particulate matter (PM), and fine particulates or PM with diameter less than or equal to 10 micrometers (PM_{10}) moderately to slightly decreased (Figure 1.1). Although PM remains at levels harmful to human health, SO_2 levels are now, on average, below the guideline values set by the World Health Organization (WHO), proving that air quality management policies and measures can work in Asia. Ambient concentrations of nitrogen dioxide (NO_2) remain at gradually increasing levels and just above the WHO guidelines.

Figure 1.1: Trends of Major Criteria Air Pollutants, 1993–2007



µg/m^3 = microgram per cubic meter, NO_2 = nitrogen dioxide, PM_{10} = particulate matter with diameter less than or equal to 10 micrometers, SO_2 = sulfur dioxide, TSP = total suspended particulates.
Note: TSP data aggregated from 17 cities; PM_{10} data from 32 cities; SO_2 data from 31 cities; and NO_2 data from 29 cities.
Source: Clean Air Initiative for Asian Cities. 2008c. Urban AQM in Asia: Status and Trends. Presented at the Fourth Regional Dialogue of Air Quality Management Initiatives and Programs in Asia, Bangkok, 30–31 January. Available: www.cleanairnet.org/caiasia/1412/article-72383.html

[1] Clean Air Initiative for Asian Cities (CAI-Asia). 2008c. Urban AQM in Asia: Status and Trends. Presented at the Fourth Regional Dialogue of Air Quality Management Initiatives and Programs in Asia, Bangkok, 30–31 January. Available: www.cleanairnet.org/caiasia/1412/article-72383.html

2. Emissions in Asia come from three main sources: stationary sources of pollution such as power plants; area sources, including road dust; and mobile sources of pollution. The relative contribution differs by city and by pollutant. The capability to develop reliable emission inventories and source apportionment studies is still limited in many parts of Asia. Scientists and policy makers have, however, acknowledged the significance of mobile sources in urban air pollution and the need to act to reduce emissions on a per vehicle basis and for the transport sector as a whole.[2] They also acknowledge the need to reduce emissions from stationary sources and area sources, including road dust.

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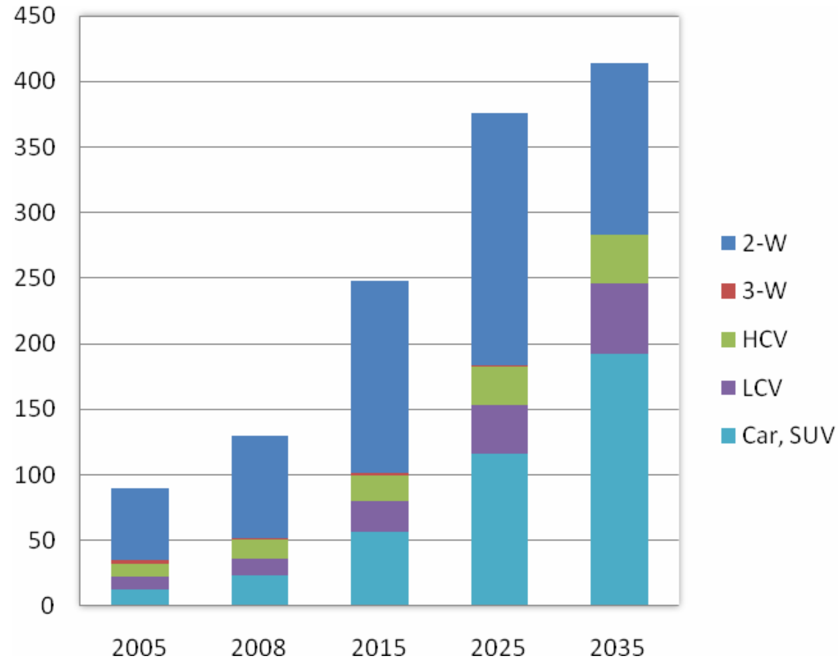
[2] Schwela, Dieter, Gary Haq, Cornie Huizenga, Wha-Jin Han, Herbert Fabian, and May Ajero. 2006 *Urban Air Pollution in Asian Cities: Status, Challenges and Management*. London: Earthscan. Available: http://shop.earthscan.co.uk/ProductDetails/mcs/productID/730. This publication is based on the Benchmarking Study on Air Quality Management Capability in Selected Asian Cities. Available: www.cleanairnet.org/caiasia/1412/article-59072.html

Figure 1.2: Forecast of Vehicle Populations in People's Republic of China
(millions of vehicles)

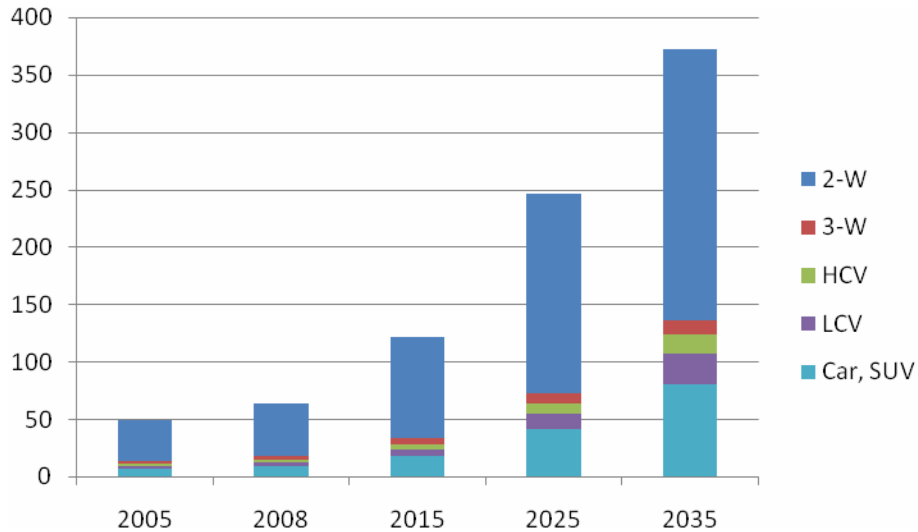


Population	2005	2008	2015	2025	2035
2-W	55.3	78.1	146.7	193.2	130.4
3-W	2	1.5	1.7	0.3	0
HCV	10.4	13.9	19.9	29.3	37.5
LCV	9.4	13.1	22.8	37.7	52.9
Car, SUV	12.9	23.4	56.8	115.8	192.7
Total	**90**	**130**	**248**	**376.4**	**413.6**

2-W = motorcycle, 3-W = three-wheeled motorcycle, HCV = heavy-duty commercial vehicle, LCV = light-duty commercial vehicle, SUV = sports utility vehicle.
Note: The forecasts are generated using Segment Y Ltd. (www.segmenty.com).
Source: Asian Development Bank (ADB). 2006. *Energy Efficiency and Climate Change Considerations for On-road Transport in Asia*. Manila : ADB. Available: www.adb.org/Documents/Reports/Energy-Efficiency-Transport/default.asp

3. Asia's rapid economic growth in recent years has triggered alike rapid growth in motorization, which is likely to continue in the years ahead. Motorization in Asia differs from the historic trends in Europe and the United States. Rather than move from nonmotorized forms of transport or public transport, as happened in most parts of Europe and the United States, many Asian countries have seen the widespread introduction of two- and three-wheeled motorized vehicles as an intermediate form of motorization (Figures 1.2 and 1.3). The increasing use of these vehicles must be reflected in vehicle emission control strategies. Developing and introducing emission standards for four-wheeled vehicles in cities like Ha Noi and Jakarta, without simultaneously issuing and enforcing stricter standards for two-wheelers, will contribute relatively little to improving urban air quality.

Figure 1.3: Forecast of Vehicle Populations in India
(millions of vehicles)

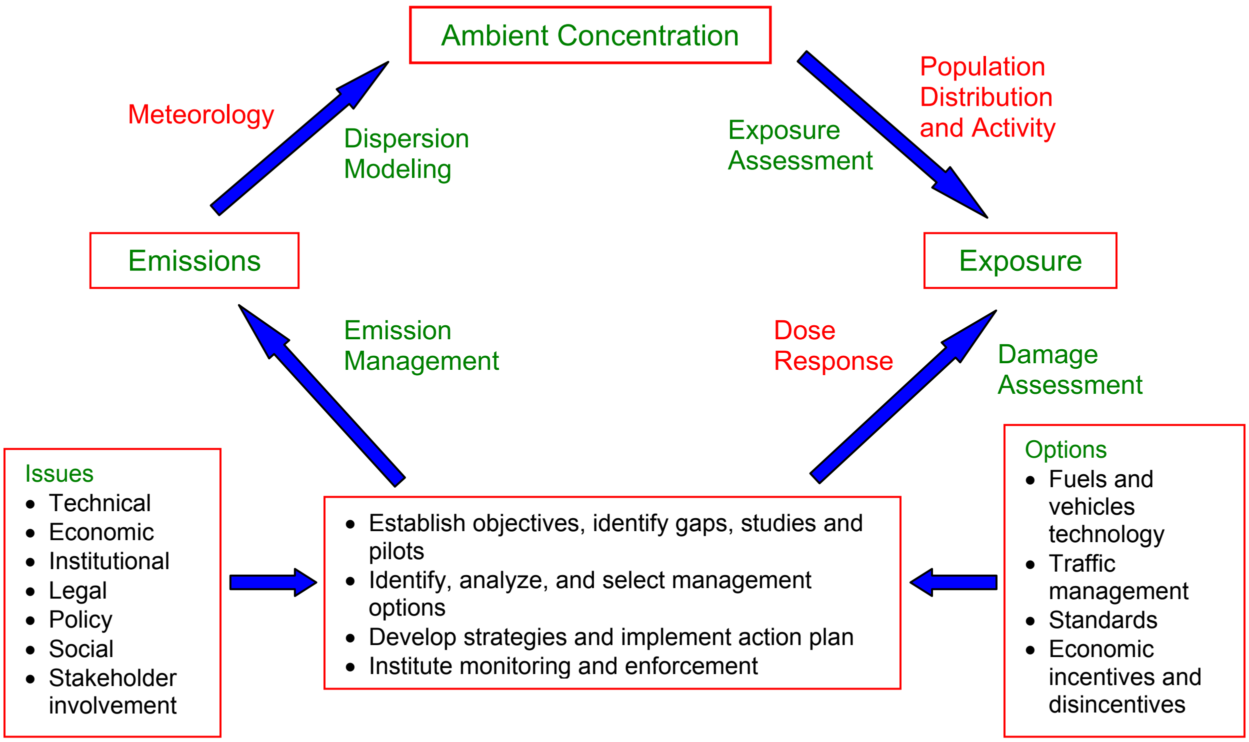


Population	2005	2008	2015	2025	2035
2-W	35.8	46.1	87.7	174.1	236.4
3-W	2.3	3	5.3	8.8	13.1
HCV	2.4	2.9	4.6	9.1	16.2
LCV	2.4	3.2	5.7	12.5	26.9
Car, SUV	6.2	8.8	18	41.6	80.1
Total	**49.1**	**63.9**	**121.3**	**246.1**	**372.7**

2-W = motorcycle, 3-W = three-wheeled motorcycle, HCV = heavy-duty commercial vehicle, LCV = light-duty commercial vehicle, SUV = sports utility vehicle.
Note: The forecasts are generated using Segment Y Ltd. (www.segmenty.com).
Source: Asian Development Bank (ADB). 2006. *Energy Efficiency and Climate Change Considerations for On-road Transport in Asia*. Manila : ADB. Available: www.adb.org/Documents/Reports/Energy-Efficiency-Transport/default.asp

4. Over the past 30 years, pollution control experts worldwide have come to agree that cleaner fuels must be a critical component of an effective clean air strategy. Cleaner fuels are fuels that result in lower emissions of air pollutants when used in motor vehicles. In recent years, this agreement on the critical role of fuels has deepened and spread to most regions of the world. Improving fuel quality is now seen not just as a necessary means to directly reduce or eliminate certain pollutants such as lead, but as a precondition for introducing many important pollution control technologies. For example, lowering sulfur content enables the use of diesel particulate filters. A critical advantage of cleaner fuels is the rapid impact these fuels have on both new and existing vehicles. Tighter new car standards can take 10 or more years to be fully effective, whereas the removal of lead in gasoline in Asia has immediately reduced lead emissions from all vehicles.

Figure 1.4: Integrated Air Quality Management Framework



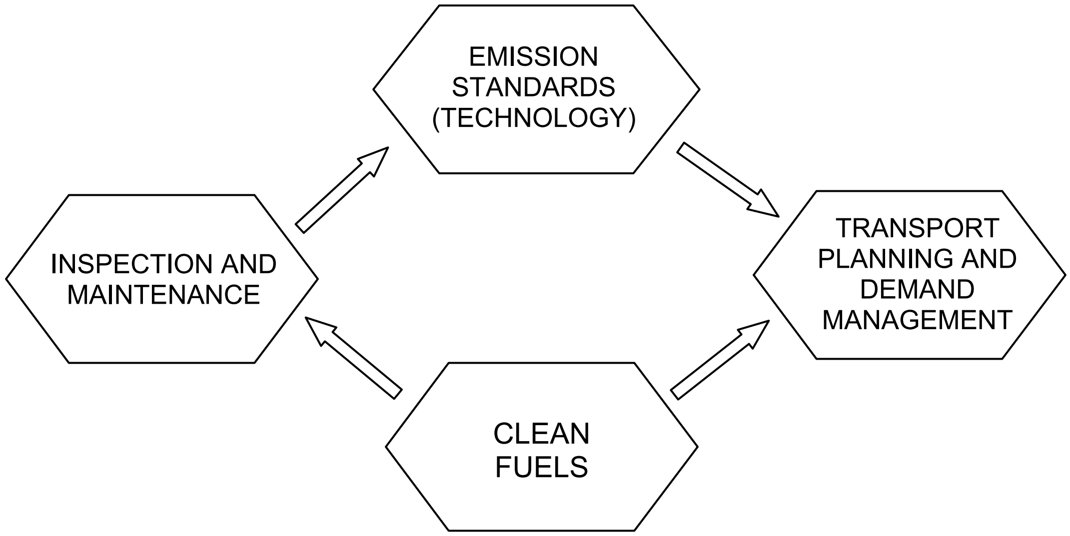
Source: Faiz, Asif. 1999. Air Quality and Transportation Strategies and Options for Controlling Motor Vehicle Pollution. Paper presented at the International Roundtable for Transportation Energy Efficiency and Sustainable Development, Cairo, 5–7 December.

5. A clear understanding of the necessary emission reductions from vehicles and other sources to achieve healthy air quality is essential in developing strategies to clean up vehicles. Depending upon the air quality problem and the contribution from vehicles, the degree of control required will differ from location to location. As Figure 1.4 illustrates, one should start with a careful assessment of air quality and the relative contributions of various categories of sources to the problem of air pollution.

6. A broad approach to the formulation and implementation of policies and actions aimed at reducing vehicular emissions is necessary where vehicles are major sources of pollution.

7. Reducing vehicular pollution will usually require a comprehensive strategy that includes these key components: (i) emission standards for new vehicles, (ii) specifications for clean fuels, (iii) programs to assure proper maintenance of in-use vehicles, and (iv) transportation planning and demand management (Figure 1.5). One critical lesson is that vehicles and fuels should be treated as a system. These emission reduction goals should be achieved in the most cost-effective manner possible. Although this report acknowledges the importance of a systems approach, it emphasizes the contribution of cleaner fuels to reducing urban air pollution.

Figure 1.5: Elements of a Comprehensive Vehicle Pollution Control Strategy



Source: Michael P. Walsh. 2004.

8. Europe, Japan, and the United States (US) began to impose vehicle emission standards in the 1960s. They have since gradually made the requirements for both new vehicles and in-use vehicles more stringent, targeting especially carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_X) for gasoline vehicles, and PM and NO_X for diesel vehicles. Although most PM emitted by vehicles is actually smaller than PM_1 (i.e., the size of particulates is smaller than one micron), the standards are not based at present on size but on mass. The introduction of cleaner fuels has made it possible to adopt increasingly stricter emission standards in Europe, Asia, and the United States, where lowering sulfur levels has been particularly instrumental in facilitating the use of advanced emission control devices required to achieve the reduced emissions on a per vehicle basis. Notwithstanding differences between Europe, Asia, and the United States in terms of fleet and driving characteristics, Asia can benefit from experiences in other parts of the world in introducing cleaner fuels and vehicles.

9. Asian countries at present do not have harmonized emission standards.[3] Although many of the countries began to develop emission standards in the 1990s, some countries, especially the smaller ones, do not yet have emission standards for new vehicles. The emphasis thus far has been on the development of emission standards for light-duty four-wheeled vehicles, followed by emission standards for two- and three-wheelers and heavy-duty vehicles. Table 1.1 indicates that the average lag time between Asia and Europe is gradually being reduced to less than 5 years for countries such as PRC; Hong Kong, China; parts of India; Singapore; and Thailand.

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[3] For purposes of this report, Asia refers to Afghanistan; Bangladesh; Bhutan; Cambodia; People's Republic of China (PRC); Hong Kong, China; India; Indonesia; Japan; Republic of Korea; Lao People's Democratic Republic (PDR); Malaysia; Myanmar; Nepal; Pakistan; Philippines; Singapore; Sri Lanka; Taipei,China; Thailand; and Viet Nam.

Table 1.1: Emission Standards for New Light-Duty Vehicles, 2008

Country	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
European Union	E1	Euro 2					Euro 3				Euro 4				Euro 5					E6
Bangladesh[a]											Euro 2									
Bangladesh[b]											Euro 1									
PRC[a]							Euro 1			Euro 2			Euro 3			Euro 4				
PRC[c]							Euro 1		Euro 2			Euro 3		Euro 4 Beijing only						
Hong Kong, China	Euro 1		Euro 2				Euro 3					Euro 4			*Euro 5*					
India[d]							Euro 1				Euro 2					Euro 3				
India[e]					E1	Euro 2					Euro 3					Euro 4				
Indonesia											Euro 2									
Republic of Korea												Euro 4			Euro 5					
Malaysia			Euro 1											*Euro 2*				*Euro 4*		
Nepal						Euro 1														
Pakistan	No conclusive information available																			
Philippines									Euro 1				Euro 2							
Singapore[a]	Euro 1						Euro 2													
Singapore[b]	Euro 1						Euro 2					Euro 4								
Sri Lanka									Euro 1				*Euro 2*							
Taipei,China					US Tier 1									US Tier 2 Bin 7[f]						
Thailand	Euro 1						Euro 2			Euro 3								Euro 4		
Viet Nam													Euro 2							

PRC = People's Republic of China.
Note: Italics indicates standards are under discussion. Standards current as of March 2008.
[a] Gasoline.
[b] Diesel.
[c] Beijing and Guangzhou adopted Euro 3 standards in September 2006, and Shanghai will do so by the end of 2008.
[d] National standard.
[e] Agra, Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Kanpur, Kolkata, Lucknow,Mumbai, Pune, Sholapur, and Surat, ; other cities in India are in Euro 2.
[f] Equivalent to Euro 4 emission standards.
Source: Clean Air Initiative for Asian Cities. 2008b. *Emission Standards for New Light-Duty Vehicles (as of 26 Mar 2008)*. Available: www.cleanairnet.org/caiasia/1412/articles-58969_resource_1.pdf

10. The European Union (EU) implemented Euro 4 standards for light-duty vehicles in 2005 and has just completed adoption of additional light-duty vehicle standards, known as Euro 5 and Euro 6, that take effect in 2009 and 2014, respectively. With respect to their own light-duty emission standards, Asian countries can be divided as follows

(i) Countries that have adopted Euro 4 emission standards in full or in part are the Republic of Korea and Taipei,China. In 2010, the entire PRC will move to Euro 4, and India will reach Euro 3 nationwide, although in those countries these standards have already been introduced in major cities such as Beijing and Delhi.[4] Malaysia and Thailand will likely reach Euro 4 light-duty standards in

[4] CAI-Asia. 2008b. *Emission Standards for New Light-Duty Vehicles (as of 26 Mar 2008)*. Available: www.cleanairnet.org/caiasia/1412/articles-58969_resource_1.pdf. Ahmedabad, Bangalore, Chennai, Delhi, Kolkata, Hyderabad, and Mumbai, have Euro 3 standards since 2005, and Beijing adopted Euro 4 in 2007.

2012.[5] Thus far, only Hong Kong, China and the Republic of Korea have indicated plans to adopt Euro 5 standards.

(ii) Countries that have developed road maps for Euro 2 but that have not finalized road maps leading to Euro 4 include Indonesia, Philippines, and Viet Nam.

(iii) Countries that have no formal fuel quality or vehicle emissions road maps in place, include Bhutan, Cambodia, Nepal, Pakistan, and Sri Lanka (footnote 4).

11. Asia has proven that it could act quickly to remove lead from gasoline given evidence of the harmful impact of lead on human health. Bans on the use of leaded gasoline were promulgated and implemented within a couple of years, except in Indonesia, which eliminated lead from gasoline nationwide only in July 2006.

Table 1.2: Current and Proposed Diesel Sulfur Levels in Asia, EU, and United States, 2008
(ppm)

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
European Union					500					50(10)[a]				10			
United States	500										15						
Bangladesh							5,000										
Cambodia					2,000				1,500								
PRC (nationwide)[a, b]	5,000						2,000			500							
PRC - Beijing	5,000						2,000		500	350			50				
Hong Kong, China		500					50					10[c]					
India (nationwide)	5,000				2,500					500					350		
India (metros)	5,000				2,500	500				350[c]					50[c]		
Indonesia	5,000										3,500				350		
Japan[d]	500									50		10					
Republic of Korea	500							430	100		30	10					
Malaysia	5,000		3,000				500[e]			500[f]							50[c]
Pakistan	10,000						7,000[e]										
Philippines	5,000					2,000			500								
Singapore	3,000		500								50						
Sri Lanka	10,000							5,000[d]			500						
Taipei,China	3,000			500			350		100				50				
Thailand	2,500			500					350		150				50		
Viet Nam	10,000											500					

EU = European Union, PRC = People's Republic of China.
[a] Various fuel quality available.
[b] Voluntary standard of 500 ppm; however, formal standard remains 2,000 ppm, product in the market nationwide varies 500-1,000 ppm.
[c] Under consideration and discussion; uncertain.
[d] National standard is 50 ppm, but industry has voluntarily achieved 10 ppm for diesel (2007) and gasoline (2008).
[e] Marketed.

[5] Department of Environment, Malaysia. 2007. *Regulation on control of petrol and diesel content 2007*. In comments from Shell to the second consultation draft of this report, Shell stated that "The Department of Environment and Ministry of Finance informed oil companies in August 2007 of the delay of Euro2M (modified) implementation. Previously, the government advised the oil industry technical committee that Euro 4M will be implemented 4 years after Euro 2M to allow time for capital investment and construction of new process unit." The "Euro2M" and "Euro 4M" references in the quote refer to Malaysia fuel standards modified from European standards.

[f] Mandatory.
Source: Clean Air Initiative for Asian Cities. 2008a. *Current and Proposed Sulfur Levels in Diesel in Asia, EU and USA (as of 27 Mar 2008)*. Available: www.cleanairnet.org/caiasia/1412/articles-40711_SulfurDiesel.pdf.

12. In line with a step-by-step tightening of vehicle emission standards, Asian countries are addressing the issue of fuel quality. The importance of linking vehicle emission standards and fuel quality standards is increasingly well-understood. Table 1.2 provides an overview of how sulfur levels in diesel are evolving in Asia as compared with those in Europe and the United States, which, as in Japan, are now moving towards levels well below 50 ppm. As with vehicle emission standards, noticeable improvements have been achieved in recent years, and several countries have formally announced the further reduction of sulfur levels to 50 ppm or less by 2012.

13. The rapid growth in motorization in Asia has affected the refining industry in Asia. After a period in which no new refining capacity was added, the PRC and India added such capacity, and plans for additional refining capacity are being discussed in those and other countries. Planning for cleaner fuels in Asia thus needs to account for the specifications of such new refineries, as well as for the specifications of existing refineries that will continue to produce the bulk of transportation fuels in the years to come.

14. CAI-Asia has taken an interest in vehicle emissions and fuel quality because of the direct relationship among vehicle emissions, air quality, and health in Asian cities. The expected continued rapid growth in the number of vehicles entering the fleet in Asian cities calls for planning and designing road maps for vehicle emission standards and fuel quality. The formulation, adoption, and implementation of such road maps can help to ensure that new vehicles entering the fleet will be covered by stricter emission standards, thereby lowering the pressure on the urban environment.

15. The discussion of fuel quality road maps supported by CAI-Asia is intended to support the processes existing in several Asian countries to develop further policies and regulations on fuel quality and vehicle emission standards.

16. The activities of CAI-Asia related to fuels and vehicle emissions[6] are guided by the same underlying principles that guide all other activities of CAI-Asia. Effective policy making requires dialogue among all stakeholders and needs to be based on sound science. A transparent process can help to increase understanding and buy-in for policy decisions. Policy processes should also be predictable so that key stakeholders can prepare properly for their implementation. Once a decision to upgrade an existing refinery or to construct a new one has been made, it can take up to 4 years for that refinery to actually begin producing cleaner fuels. The need for transparency and predictability underscores the importance of developing fuel quality road maps for Asian countries to guide investment decisions in the refining and vehicle manufacturing industry.

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[6] Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Prepared by Enstrat International, Ltd. Manila: ADB. Available: www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf. CAI-Asia and the International Fuel Quality Center, with support from the Australian Department of Environment and Heritage, held a Fuel Quality Strategy Training Workshop in the last quarter of 2003 and produced five modules on the subject. Available: www.cleanairnet.org/caiasia/1412/article-58140.html

17. CAI-Asia intends that this report, *A Road Map for Cleaner Fuels and Vehicles in Asia*, gather information in a structured manner and help shape fuel road maps in Asian countries. This report focuses on fuels and assumes that the availability of new vehicles that can comply with stricter emission standards will not be a constraining factor. To promote successfully cleaner fuels succeed and contribute to the improvement of urban air quality in Asian cities, CAI-Asia recommends the following measures:

(i) Adopt an integrated approach that includes mobile, stationary, and area sources of pollution.[7]

(ii) Address emissions from both new and in-use vehicles, and combine traffic demand management with tailpipe solutions to prevent and reduce emissions,[8] such that appropriate attention is given to two- and three-wheeled vehicles in countries where such vehicles form an important part of the vehicle fleet.

(iii) Build on the current status of fuel quality standards and ongoing discussions in various Asian countries.

18. This road map report for cleaner fuels and vehicles for Asia deals with gasoline and diesel. Biofuels are an important alternative source of transport fuel, as are compressed natural gas (CNG) and liquefied petroleum gas (LPG). However, the use and production of these alternative fuels is outside the scope of this report. Increased attention to these fuels, both in Asia and elsewhere, merits a separate study.[9] Technologies such as coal-to-liquid and gas-to-liquid are also not addressed in this report. In addition, this report focuses on emission related characteristics of transport fuels. Other important characteristics, such as safety, driveability, and fuel economy need to be considered in formulating fuel quality improvement strategies. These fall, however, outside the scope of this report and will not be dealt with in detail.

19. Chapter 2 contains an extensive overview of the relationships between vehicle engine technology, including emission control devices, and fuel characteristics and vehicle emissions. Chapter 3 analyzes the costs of producing cleaner fuels in Asia. Chapter 4 assesses the impacts of the use of octane enhancing additives on health and vehicle emissions. Chapter 5 describes the role of pricing, taxation, and incentives in promoting the use of cleaner fuels. Chapter 6 concludes the report with recommendations on the timing and approach in introducing cleaner fuels in Asia.

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[7] Stockholm Environment Institute, Korea Environment Institute, Ministry of Environment—Korea. 2004. *A Strategic Framework for Air Quality Management in Asia*. Manila. Available: www.cleanairnet.org/caiasia/1412/article-58180.html

[8] Please see (i) ADB. 2003b. *Policy Guidelines for Reducing Vehicle Emissions in Asia*. Manila: ADB; (ii) World Bank. 1991. *Environmental Assessment Sourcebook and Updates*. Washington, DC: World Bank. Available: http://go.worldbank.org/LLF3CMS1I0; (iii) GTZ. 2004. *Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities: Module 5a, Air Quality Management*. Eschborn: GTZ. Available: www.gtz.de/en/dokumente/en-air-quality-management2004.pdf

[9] Such additional studies will have to consider, among other factors, the feedstock of biofuels to ensure that air quality benefits are not compromised by increases in greenhouse gas emissions due to direct and indirect land use conversions in support of biofuel production.

II. FUELS AND VEHICLES

A. Introduction

20. Motor vehicles emit large quantities of CO, HC, NO_X, PM, carbon dioxide (CO_2), and toxic substances such as benzene, formaldehyde, acetaldehyde, 1,3-butadiene, and lead. Along with secondary by-products, such as ozone, all of these can seriously harm human health and the environment. A growing vehicle population and the high emission levels of many of these vehicles, contribute to the serious air pollution and health problems increasingly common in the cities of developing countries, including those in Asia.

21. Extensive studies over the last 30 years have helped to establish the linkages between fuels, vehicles, and vehicle emissions. One major study, the auto/oil air quality improvement research program was established in 1989 in the United States and involved 14 oil companies, three domestic automakers, and four associate members.[10] The European Commission initiated Europe's own vehicle emissions and air quality program in 1992. The motor industry (represented by the European Automobile Manufacturers Association [ACEA]) and the oil industry (European Petroleum Industry Association) were invited to cooperate within a framework program, later known as "the tripartite activity" or European auto/oil program. The two industries signed a contract in 1993 to undertake a common test program, called the European programmes on emissions, fuels and engine technologies (EPEFE).

22. Supported by Japan's Ministry of Economy, Trade and Industry, the Japan Clean Air Program (JCAP) was conducted by Petroleum Energy Center as a joint research program of the automobile industry (as fuel users) and the petroleum industry (as fuel producers). The first stage of the program, called JCAP I, began in 1997 and ended in 2001; the second, called JCAP II, began in 2002 and continued until 2007 to provide a further development of the research activities of JCAP I. Studies in JCAP II focused on future automobile and fuel technologies aimed at realizing zero emissions while improving fuel consumption. The program focused on studies of fine particles in exhaust emissions.

23. This chapter relies heavily on each of these studies, as well as on other recent work, in summarizing what is known about the impact of fuel quality on emissions.

24. It is useful to summarize EU fuel quality specifications, as most Asian countries have linked their vehicle emission control programs to the EU or the Economic Commission for Europe requirements. These specifications can usefully be described in terms of four classes: effectively Euro 2, 3, 4, and 5. The Euro 2 fuel sulfur level was set at 500 ppm to improve the performance of the catalytic converters used on gasoline vehicles, which were expected to be introduced for some diesel vehicles. Specifications for the Euro 3 and 4 standards have been set with particular attention to the "environmental qualities" of the fuel, to allow for a further tightening of sulfur levels to improve the performance or, in some cases, allow the use of advanced pollution control technologies. Table 2.1 details the specifications for the key environmental Euro 3, 4, and 5 fuel parameters. The only change in the specifications for Euro 4 diesel was to establish the sulfur content at 50 ppm. The Economic Commission for Europe had intended for the standard to include other changes, but these were not made because of

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[10] Society of Automotive Engineers (SAE). 1997. *Auto/Oil Air Quality Improvement Research Program, Final Report*. Detroit.

insufficient resources. While the maximum sulfur limit of 50 ppm applied to all gasoline and diesel fuel sold in the EU in 2005, fuels with a maximum limit of 10 ppm were to be widely available by that year. The introduction of the Euro 5 emission standard in 2009 will further lower sulfur levels in both gasoline and diesel to 10 ppm and lower olefins in gasoline to 13% and polyaromatics in diesel to 6%. Discussions are ongoing concerning the detailed fuel specifications for the Euro 6 emission standard to be implemented by 2014.

Table 2.1: EU Gasoline and Diesel Fuel Quality Specifications

	Euro 3	Euro 4	Euro 5[a]		Euro 3	Euro 4	Euro 5[b]
Petrol/Gasoline	**2000**	**2005**	**2009**	**Diesel**	**2000**	**2005**	**2009**
RVP summer kPa, max.	60	60	60	Cetane number, min.	51	51	52
Aromatics, % by vol. max.	42	35	35	Density 15 °C kg/m³, max.	845	845	837
Benzene, % by vol. max.	1	1	1	Distillation 95% by vol. °C, max.	360	360	350
Olefins, % by vol. max.	18	18	13	Polyaromatics, % by vol., max.	11	11	6
Oxygen, % by mass max.	2.7	2.7	2.7	Sulfur, ppm max.	350	50	10
Sulfur, ppm	150	50	10				

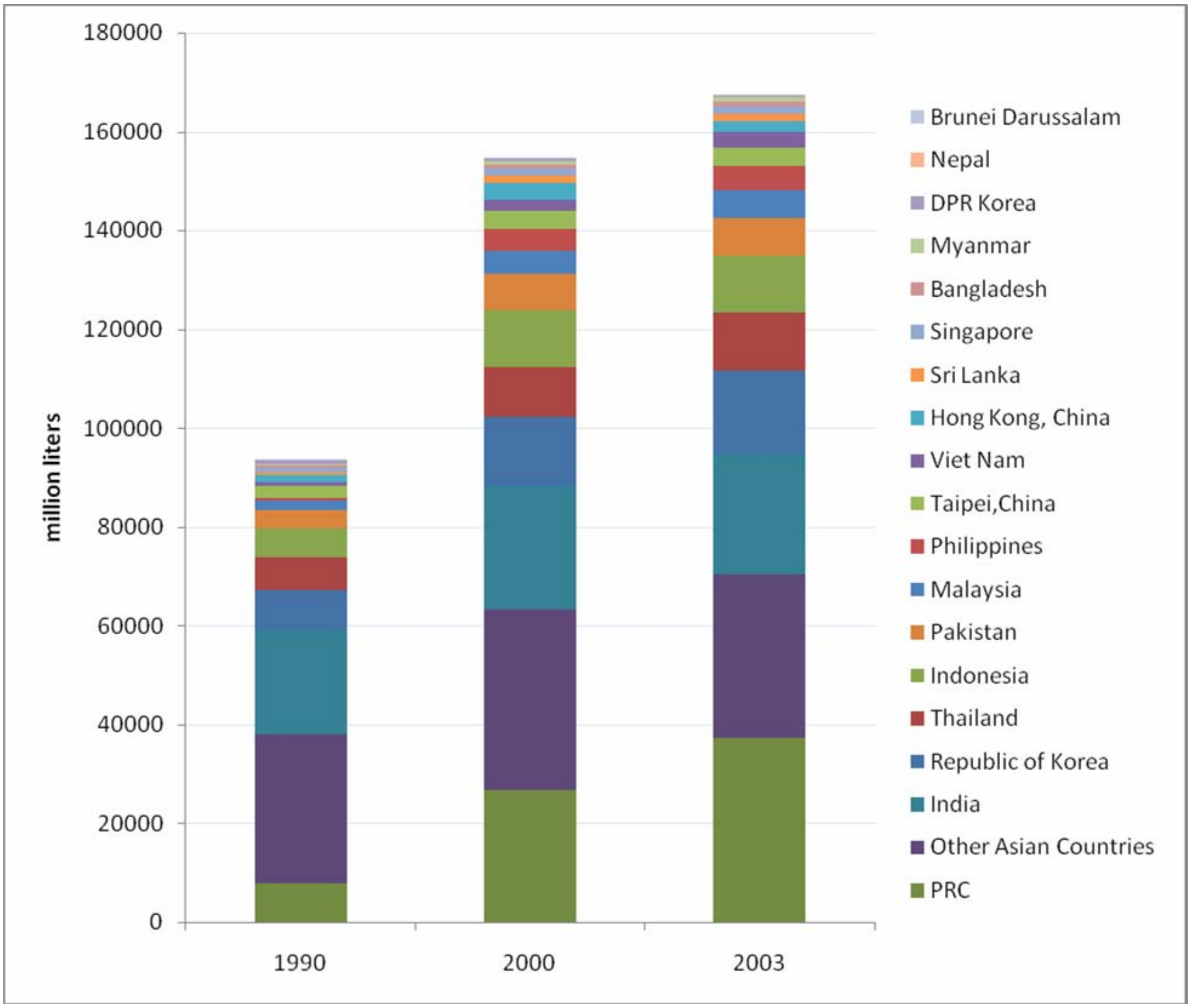
°C = degrees Celsius, EU = European Union, kg/m^3 = kilograms per cubic meter, kPa = kilopascals, where 1 atmosphere of pressure equals about 100 kPa, max. = maximum, min. = minimum, ppm = parts per million, RVP = Reid vapor pressure, vol. = volume.
[a] Ethanol mix minimum of 4.7% by volume and maximum of 5.3% by volume.
[b] TAME mix minimum of 4.5% by volume and maximum of 5.5% by volume.
Source: European Parliament and Council. 13 October 1998. *Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 Relating to the Quality of Petrol and Diesel Fuels and Amending Council Directive 93/12/EEC*. Available: http://eur-lex.europa.eu/ LexUriServ/site/en/consleg/1998/L/01998L0070-20031120-en.pdf; www.ec.europa.eu/enterprise/ automotive/catp_meetings/agenda91/euro_5_and_6_comm_regulation.pdf

B. Diesel Vehicles and Fuels

1. Importance of Diesel as a Transportation Fuel in Asia

25. Diesel fuel usage in Asia has risen dramatically over the past three decades and shows every sign of continuing to do so in the years ahead. As Figure 2.1 indicates, although there was a slight decline during the economic downturn of the 1990s, the growth in diesel consumption has more than resumed. The projections in Table 2.2 show that in Asia diesel will continue to have a larger market share compared to that in Organisation for Economic Co-operation and Development (OECD) countries or the world in general.

Figure 2.1: Annual Diesel Fuel Consumption Trends in Asia
(in million liters)



DPR Korea = Democratic People's Republic of Korea, PRC = People's Republic of China.
Source: International Energy Agency (IEA) Statistics Division. 2006. Energy Balances of OECD Countries (2006 edition)--Extended Balances and Energy Balances of Non-OECD Countries (2006 edition)--Extended Balances. Paris: IEA. Available: http://data.iea.org/ieastore/default.asp

26. Diesel fuel receives favorable tax status in many countries as it tends to be the fuel of commerce, used in diesel trucks and in most transit buses. In addition, as diesel became comparatively more attractive in the 1980s it became the predominant fuel for certain specialized transit vehicles, such as jeepneys in the Philippines, which had until then been almost exclusively gasoline fueled.

Table 2.2: Diesel Fuel Consumption Trends in Asia

Country or Region	Diesel Fuel Consumption of On-Road Vehicles as Percentage of All Fuels				
	2005	**2010**	**2015**	**2020**	**2025**
PRC	32	31	29	28	27
India	64	63	60	58	57
Other Emerging Asia	55	55	54	53	53
Emerging Asia	51	50	49	47	45
OECD (for reference)	33	34	35	36	36
World Total	**36**	**37**	**38**	**38**	**38**

OECD = Organisation for Economic Co-operation and Development, PRC = People's Republic of China.
Source: International Energy Agency – Sustainable Mobility Project transport model reference case projections in Asian Development Bank (ADB). 2006. *Energy Efficiency and Climate Change Considerations for On-road Transport in Asia*. Manila : ADB. Available: www.adb.org/Documents/Reports/Energy-Efficiency-Transport

27. Many Asian countries, including the PRC, Republic of Korea, and Taipei,China historically have restricted the use of diesel in private cars so that the lower tax on diesel fuel would not distort the light-duty vehicle marketplace. These restrictions have recently been lifted in preparation for entry of these countries into the World Trade Organization.

28. Diesel vehicles emit significant quantities of both NO_X and PM. The highest regulatory priority has been to reduce PM emissions from diesel vehicles because PM emissions in general are very hazardous and diesel PM, especially, is likely to cause cancer. Reducing NO_X emissions is also important, however, as such emissions cause or contribute to ambient nitrogen dioxide, ozone, and secondary PM (nitrates). For instance, NO_X and other pollutants that are emitted from vehicles as gases undergo transformation in the atmosphere and are converted into particles. Some of the gaseous NO_X emitted from vehicles reacts chemically with other gases and is converted into nitrates, which contribute to urban PM air quality levels.

29. The growing awareness of the health risks from diesel vehicle emissions, especially those of diesel PM, has led to efforts in some Asian countries to constrain diesel usage. Cities such as Beijing and Delhi have converted some or all of their buses to operate on CNG because of these serious diesel health consequences. Hong Kong, China has retrofitted many of its trucks and buses with particulate control devices[11] and has required most taxis to use LPG instead of diesel.

2. General Description of Diesel Fuel Parameters

30. Diesel fuel is a complex mixture of hydrocarbons, consisting primarily of paraffins, napthenes, and aromatics. Organic sulfur is also naturally present. Additives are generally used to influence properties such as the flow, storage, and combustion characteristics of diesel fuel. The actual properties of commercial automotive diesel depend on the refining practices employed and on the nature of the crude oils from which the fuel is produced. The quality and composition of diesel fuel can significantly influence emissions from diesel engines.

[11] Hong Kong, China reduced the sulfur content in diesel fuel to a maximum of 50 ppm prior to retrofitting vehicles.

31. To reduce PM and NO_X emissions from a diesel engine, the most important fuel characteristic is sulfur because sulfur contributes directly to PM emissions, and high sulfur levels preclude the use of or impair the performance of the most effective PM and NO_X control technologies. For the control of PM, most new vehicles in Japan, the United States, and a growing number of European countries are equipped with filters or traps that reduce over 90% of the particles. NO_X adsorbers and selective catalytic reduction (SCR) systems are also being introduced, with the former especially sensitive to sulfur levels in the fuel. (See section 5 of this chapter for a more detailed discussion of diesel control technology.)

3. Impact of Diesel Fuel Composition on Asian Vehicle Emissions

32. Tables 2.3 and 2.4 summarize the impacts of various diesel fuel qualities on emissions from light- and heavy-duty diesel vehicles, respectively.

Table 2.3: Impact of Fuels on Light-Duty Diesel Vehicles

Diesel Fuel Characteristic	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5[a]	Comments
Sulfur$\uparrow$	SO_2, PM$\uparrow$		If oxidation catalyst is used, SO_3, SO_2, PM$\uparrow$		If filter, 50 ppm maximum, 10–15 ppm better		If NO_X adsorber used requires near zero sulfur (<10 ppm). With low S, use lubricity additives.
Cetane$\uparrow$	Lower CO, HC, benzene, 1,3 butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels.
Density$\downarrow$	PM, HC, CO, formaldehyde, acetaldehyde & benzene$\downarrow$, $NO_X$$\uparrow$						
Volatility (T95 from 370 to 325 °C)	NO_X, HC$\uparrow$, PM, CO$\downarrow$						
Polyaromatics$\downarrow$	NO_X, PM, formaldehyde & acetaldehyde$\downarrow$ but HC, benzene & CO$\uparrow$						Some studies show that total aromatics are important for emissions in a manner similar to polyaromatics.

°C = degrees Celsius, CO = carbon monoxide, HC = hydrocarbons, NO_X = nitrogen oxides, PM = particulate matter, ppm = parts per million, S = sulfur, SO_2 = sulfur dioxide, SO_3 = sulfur trioxide, an intermediate compound, T95 = temperature at which 95% of the diesel distills.

[a] Euro 5 emission standards for light-duty diesel vehicles have recently been adopted by the EU for implementation in 2009; Euro 6 limits were also adopted for 2014 implementation. Both Euro 5 and Euro 6 standards are intended to mandate the use of PM filters on all light-duty diesel vehicles.

Source (for note a only): European Union. 2007. *Euro 5 and Euro 6 Standards: Reduction of Pollutant Emissions from Light Vehicles. Regulation (EC) No715/2007*. Strasbourg. Available: http://europa.eu/scadplus/leg/en/lvb/l28186.htm

Table 2.4: Impact of Fuels on Heavy-Duty Diesel Vehicles

Diesel	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5[a]	Comments
Sulfur↑	SO_2, PM↑		If oxidation catalyst is used, SO_3, SO_2, PM↑		If filter, 50 ppm maximum, 10–15 ppm better		If NO_X adsorber used requires near zero sulfur (<10 ppm). With low S, use lubricity additives.
Cetane↑	Lower CO, HC, benzene, 1,3-butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels.
Density↓	HC, CO↑, NO_X↓						
Volatility (T95 from 370 to 325 °C)	Slightly lower NO_X, but HC↑						Too large a fraction of fuel that does not volatilize at 370 °C increases smoke and PM.
Polyaromatics↓	NO_X, PM, HC↓						Some studies show that total aromatics are important.

°C = degrees Celsius, CO = carbon monoxide, HC = hydrocarbons, NO_X = nitrogen oxides, PM = particulate matter, ppm = parts per million, S = sulfur, SO_2 = sulfur dioxide, SO_3 = sulfur trioxide, an intermediate compound, T95 = temperature at which 95% of the diesel distills.

[a] The EU Commission proposed Euro 6 emission standards for heavy-duty engines in December 2007, mandating the use of PM filters on all heavy-duty diesel vehicles from 2014.

Source (for note a only): European Union. 2007. *Euro 5 and Euro 6 Standards: Reduction of Pollutant Emissions from Light Vehicles. Regulation (EC) No715/2007*. Strasbourg. Available: http://europa.eu/scadplus/leg/en/lvb/l28186.htm

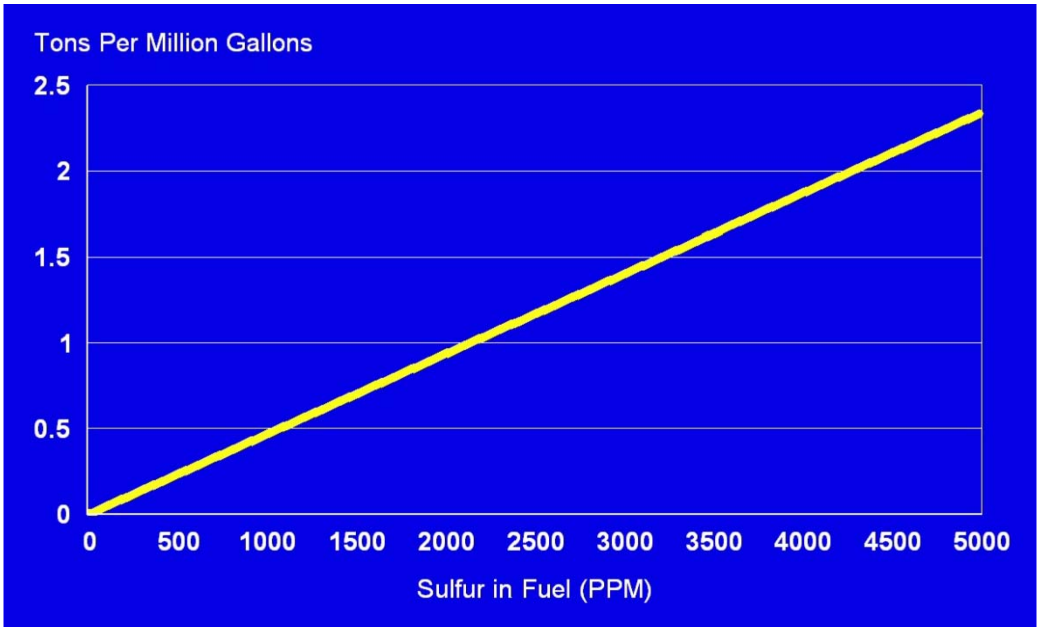
4. Changes in Diesel Fuel Parameters in Asia to Achieve Lower Emissions

a. Sulfur

33. Sulfur occurs naturally in crude oil, and the sulfur content of diesel fuel depends on both the source of the crude oil and the refining process.

34. The contribution of the sulfur content of diesel fuel to exhaust particulate emissions has been well established, with a general linear relationship between fuel sulfur levels and this regulated emission. Figure 2.2 estimates this relationship based on data provided by the United States Environmental Protection Agency (US EPA). (This figure shows only the sulfur-related PM and not the total PM emitted from a diesel engine.) An indirect relationship also exists, as some emissions of SO_2 will eventually be converted in the atmosphere to sulfate PM, in a manner similar to the secondary transformation of NO_X to nitrate discussed earlier.

Figure 2.2: Tons of Directly Emitted PM from Sulfur in Diesel Fuels



PM = particulate matter
PPM = parts per million.
Note: Only PM related to sulfur and not the total PM emitted from a diesel engine is reflected in this figure.
Source: Calculated from data provided by the United States Environmental Protection Agency.

35. Light-duty diesel engines (<3,500 kilograms of gross vehicle weight) generally require oxidation catalysts in order to comply with Euro 2 or more stringent vehicle emission standards. Oxidation catalysts lower HC, CO, and PM, typically removing around 30% of total particle mass emissions through oxidation of a large proportion of the soluble organic fraction. The conversion of sulfur in the catalyst reduces the availability of active sites on the catalyst surface, thus reducing catalyst effectiveness. This sulfur catalyst "poisoning" is reversible through high temperature exposure in which the sulfur compounds decompose and are released from the catalyst washcoat. However, due to generally low diesel exhaust temperatures, in many diesel engine applications the conditions needed for full catalyst regeneration may rarely be attained. High sulfur content in the fuel can also deposit sulfates in the converter that are then emitted as additional particles.

36. Tighter limits on the maximum sulfur content of commercial diesel fuel have been, or are being, introduced in many countries to enable compliance with tighter PM emission standards for diesel vehicles (Table 1.2). Although PM can be substantially reduced without reducing sulfur levels, it is generally not possible to comply with Euro 2 or tighter vehicle emission standards when fuel sulfur levels are greater than 500 ppm because of the relatively greater proportion of sulfates in the total mass of PM.

37. NO_X control systems for diesel vehicles are still evolving. The two prime candidates for Euro 4 and Euro 5 vehicles are SCR systems and NO_X aftertreatment devices. Although SCR systems are not particularly sensitive to sulfur levels, they tend to be combined with an oxidation catalyst to reduce ammonia slip. These oxidation catalysts are sensitive to sulfur levels and will also tend to increase sulfate emissions levels. NO_X aftertreatment devices are extremely sensitive to sulfur and require levels in the range of 10 (Euro 5) to 15 ppm or less.

38. Sulfur content is also known to increase engine wear and deposits, but this appears to vary considerably in significance depending largely on operating conditions. High sulfur content becomes a problem when diesel engines operate intermittently or at low temperatures. Under these conditions there is more moisture condensation, which combines with sulfur compounds to form acids, and cause corrosion and excessive engine wear. Generally, the lower the sulfur levels, the less the engine wear.

39. Diesel fuel has natural lubricity from compounds that include the heavier hydrocarbons and organo-sulfur. Diesel fuel pumps, especially rotary injection pumps in light-duty vehicles, without an external lubrication system, rely on the lubricating properties of the fuel to ensure proper operation. Refining processes that remove sulfur and aromatics from diesel fuel tend to also reduce the components that provide natural lubricity.

40. In addition to causing excessive pump wear and, in some cases, engine failure, certain modes of deterioration in the injection system could also affect the combustion process, and hence emissions. Additives are available to improve lubricity with very low sulfur fuels and should be used with any fuel with 50 ppm sulfur or less.

b. Cetane

41. Cetane number is a measure of auto-ignition quality that depends on fuel composition and relates to the delay between fuel injection into the cylinder and ignition. It influences the performance of vehicles in cold starts, exhaust emissions, and combustion noise. Rapidly igniting fuels have high cetane numbers of 50 or above. Slowly igniting fuels have low cetane numbers of 40 or below. The cetane number for aromatic hydrocarbons is low, while it is high for paraffins and falls somewhere between the two for napthenes.

42. The cetane index indicates the natural cetane of the fuel. It is calculated based on the fuel density and distillation parameters. Although the index estimates the base auto-ignition quality of the fuel, it does not indicate the effects of cetane improver additives.

43. The EPEFE study documents experiments showing that an increase in cetane number decreases CO and HC emissions (notably from light-duty engines), NO_X emissions (notably from heavy-duty engines), and a decrease in benzene, 1,3-butadiene, formaldehyde, and acetaldehyde emissions (notably from light-duty engines).

44. Although the EPEFE study found that PM increased from light-duty vehicles as the cetane number increased (no significant effect was seen in heavy-duty engines), other research has suggested that an increase in cetane number can lower PM. It is generally agreed that the higher the cetane number, the better.

45. Cetane number requirements for diesel vehicles depend on the engine design and size, the nature of speed and load variations, and starting and atmospheric conditions. High cetane number fuels enable an engine to be started more easily at lower air temperatures, reduce white smoke exhaust, and reduce diesel knock. With a low cetane number fuel, engine knock noise and white smoke can be observed during engine warm-up, especially in severe cold weather (as occurs, for example, in parts of the PRC). If this condition continues for any prolonged period, harmful fuel-derived deposits will accumulate within the combustion chamber. While an engine may appear to operate satisfactorily on low cetane number fuel, severe mechanical damage, such as piston erosion, can result after prolonged use.

46. An increase in natural cetane can help reduce fuel consumption. To avoid excessive dosage with cetane additives, the World Wide Fuel Charter recommends that the difference between the cetane index and the cetane number be no greater than three. This has been the general practice. Large quantities of additive usually are not added because of the expense.

c. Density

47. The higher the density of a fuel, the higher its energy content per unit volume. The density of diesel fuel largely depends on its chemical composition. Higher density frequently indicates a high aromatic content in diesel fuel, for a given distillation range. Increased aromatic content is known to lead to increase PM. Too high a fuel density for the engine calibration has the effect of over-fuelling, thus increasing black smoke and other gaseous emissions.

48. The EPEFE study found that for light-duty vehicles, reducing fuel density decreased emissions of PM, HC, CO, formaldehyde, acetaldehyde, and benzene; increased emissions of NO_X; and had no impact on the composition of the particle load. For heavy-duty vehicles, reducing fuel density decreased emissions of NO_X; increased emissions of HC and CO; and had no impact on PM emissions or the composition of the particle load.

49. The EPEFE study also investigated the extent to which the observed density effects on emissions could be decreased by tuning the engine management system to fuel density. The test results indicated that the effect of density on engine emissions is, to a certain extent, caused by the physical interaction of fuel density with the fuel management system. Some density effects still remained after engines were calibrated to specific fuels.

50. Density levels are also influenced by T95 distillation maximum limits (discussed in more detail below) through their impact on the heavy fractions of the fuel. A T95 limit is the temperature at which 95% of the fuel will evaporate, or distill. These limits could also be adjusted to compensate for density impacts.

d. Distillation Characteristics (Volatility)

51. Distillation refers to the volatility profile of diesel fuel. The distillation or boiling range of the fuel depends on the chemical composition of the fuel as it is adjusted to meet other fuel property requirements such as viscosity, flash point, cetane number, and density, within a particular refinery's overall product slate.

52. Volatility can influence the amount and kind of exhaust smoke that is emitted. Correct distillation characteristics are therefore essential for efficient fuel combustion. These characteristics are achieved by carefully balancing the light and heavy fuel fractions (parts) during refining. Heavy fractions have high energy content and improve fuel economy, but they can cause harmful deposit formation inside engines. Light fractions reduce the overall viscosity to improve fuel injection atomization, engine starting, and complete combustion under a variety of engine conditions, but they do not have as much energy per unit volume of fuel (i.e., density) as heavier fractions.

53. The distillation curve of diesel fuel indicates the amount of fuel that will boil off at a given temperature. The curve can be divided into three parts: the light end, which affects startability; the region around the 50% evaporated point, which is linked to other fuel parameters such as viscosity and density; and the heavy end, characterized by T90 (temperature at which 90% of the fuel will evaporate), T95, and final boiling point.

54. Investigations have shown that too much "heavy ends" in the fuel's distillation curve can result in heavier combustion chamber deposits and increased tailpipe emissions of soot, smoke, and PM. The effect of T95 on vehicle emissions was examined in the EPEFE study, which indicated that exhaust gas emissions from heavy-duty diesel engines were not significantly influenced by T95 variations between 320°C and 375°C. However, a tendency for lower NO_X and higher HC emissions with lower T95 was observed.

e. Polycyclic Aromatic Hydrocarbons (PAHs)

55. Crude oils contain a range of hydrocarbons including polynuclear aromatic hydrocarbons or polyaromatic hydrocarbons (PAHs), which are heavy organic compounds found mostly in diesel PM but which can also be present in the gas phase.

56. Higher aromatic content in the fuel degrades auto-ignition quality, increases thermal cracking and peak flame temperatures, and delays combustion processes. From a combustion perspective, aromatics are generally a poor diesel fuel component.

57. PAHs are drawing increasing attention because many are known human carcinogens. Testing for the EPEFE study demonstrated that a reduction in the total aromatic content of diesel significantly lowers NO_X, PM, CO, benzene, formaldehyde, and acetaldehyde emissions.

58. The EPEFE study indicated that reducing polyaromatics decreased NO_X, PM, formaldehyde, and acetaldehyde emissions, but increased HC, benzene, and CO emissions for light-duty vehicles; and reducing polyaromatics decreased NO_X, PM, and HC emissions for heavy-duty vehicles.

f. Ash and Suspended Solids

59. Ash-forming materials, that is, incombustible mineral material, may occur in diesel fuel in two forms: as suspended solids or as hydrocarbon soluble organo-metallic compounds.

60. Ash-forming suspended solids may contribute to fuel injector and fuel pump wear, which are critical issues in the engines required to meet tighter emission standards. Ash-forming soluble organo-metallic compounds have little effect on wear of these components; however, as with suspended solids, they can contribute to combustion chamber deposits, most critically on fuel injector tips, which can then impair emissions performance, especially with regard to fine particles.

61. Although levels of suspended solids may be substantially reduced by engine fuel filters, dissolved organo-metallic compound levels are not, and they require management by other means.

62. The use of recycled waste oil as diesel extender may potentially increase the ash content of the fuel.

g. Viscosity

63. The viscosity of a fluid indicates its resistance to flow—the higher the viscosity, the greater the resistance. Along with density and distillation range, viscosity is an important characteristic of fuel.

64. Viscosity of diesel fuel is important for operating the fuel injection equipment required to measure accurately small quantities of fuel prior to injection and to atomize the fuel in the injection process.

65. Fuel with low viscosity can excessively wear down some injection pumps and cause power loss from pump injector leakage. Spray may not atomize sufficiently, thereby impairing combustion and decreasing power output and fuel economy. This condition can worsen emissions.

5. Emission Control Technology for Diesel Vehicles

66. Diesel vehicles emit high levels of NO_X and PM as noted earlier. Modifying engine parameters to simultaneously reduce both NO_X and PM is difficult and limited as the optimal settings for one pollutant frequently increase emissions of the other, and vice-versa. Modest to significant NO_X control can be achieved by delaying fuel injection timing and adding exhaust gas recirculation (EGR). Very high-pressure, computer-controlled fuel injection can also be timed to reduce PM emissions. But very low levels of NO_X and PM require exhaust treatment. Evolving technologies such as lean NO_X catalysts, SCR, NO_X storage traps with periodic reduction, filter traps with periodic burn-off, and oxidation catalysts with continuous burn-off are being phased in at differing rates in various parts of the world. For example, Japan generally leads the world in the widespread use of PM filters on new diesel vehicles, while Europe generally lags behind. However, some European countries are using tax incentives to accelerate the introduction of PM filters beyond the rate required by the Euro new vehicle standards. A new type of diesel engine, the homogeneous charge compression ignition engine, is another means to reduce NO_X and PM. This technology is receiving significant attention and may be introduced within a few years for at least portions of the engine map on some engines.

67. As noted earlier, reformulated diesel fuels can effectively reduce NO_X and PM emissions from all diesel vehicles. These fuels have reduced sulfur and aromatics and an increased cetane number. However, certain technologies are especially sensitive to the sulfur content of the fuel. The linkages between sulfur and diesel vehicles technologies will be summarized below.

a. No Controls and Pre-Aftertreatment Controls

68. For diesel vehicles with no controls, fuel sulfur levels directly impact SO_2 and PM emissions (some SO_2 emissions are converted in the atmosphere to sulfate PM.) SO_2 emissions are directly proportional to the amount of sulfur contained in the fuel. Although total PM emissions are proportional to the amount of sulfur in diesel fuel, the carbon and the soluble organic fractions are not. In the oxygen-rich exhaust of diesel vehicles, several percent of the SO_2 formed during combustion is oxidized to sulfurtrioxide, which dissolves in the water vapor present to form vaporous sulfuric acid. This sulfuric acid forms ultrafine particles in diesel exhaust that are considered especially hazardous because of their ability to penetrate deeply into the lungs. Even though sulfate particles account for only a small fraction of particle volume or mass, they account for a sizeable proportion of PM.

69. According to US EPA, approximately 2% of the sulfur in diesel fuel is converted to direct PM emissions. In addition, SO_2 emissions can lead to secondary particle formation in the ambient air. US EPA models predict that over 12% of the SO_2 emitted in urban areas is converted in the atmosphere to sulfate PM. Urban areas would benefit most from reductions in SO_2 emissions, as polluted urban air has higher concentrations of the constituents that catalyze

the SO_2-to-sulfate reaction. Reductions of fuel sulfur levels would likely reduce significantly primary and secondary PM concentrations in urban areas, even for vehicle stocks without advanced pollution controls.

b. Post Combustion Controls

70. With high fuel sulfur levels, diesel catalysts produce correspondingly high levels of hazardous sulfate. Advanced catalyst technologies, such as NO_X adsorbers, are precluded by high levels of sulfur. PM filter performance likewise is impaired by higher levels of sulfur.

i. Diesel Oxidation Catalysts

71. Diesel oxidation catalysts (DOCs) are currently the most common aftertreatment emission control technology in diesel vehicles. DOCs resemble the earliest catalysts used for gasoline engines. Oxidation catalysts work by oxidizing CO, HC, and the soluble organic fraction of the PM to CO_2 and water in the oxygen-rich exhaust stream of the diesel engine.

72. When sulfur is present in the fuel, DOCs also increase the oxidation rate of SO_2, leading to increases in emissions of ultrafine PM sulfates. Sulfate conversion depends on overall catalyst efficiency, with more efficient catalysts capable of converting nearly 100% of the SO_2 in the exhaust to sulfate. Generally, one should restrict the use of DOCs to areas which have fuel sulfur levels of 500 ppm or below. With low sulfur fuel, a DOC can reduce PM emissions by 25% to 30%.

ii. Diesel Particulate Filters

73. Diesel particulate filters reliably demonstrate over 95% efficiency with near-zero sulfur fuel use, and can reduce the total number of particles emitted to levels similar to or even slightly lower than those of gasoline engines. One important area of research is the passive regeneration or cleaning of the collected particles from the filter surface, a process very sensitive to sulfur levels. Filters need to be cleaned, ideally without human intervention, before reaching capacity in order to maintain vehicle performance and fuel and filter efficiency.

74. The continuously regenerating diesel particulate filter and the catalyzed diesel particulate filter are two examples of PM control with passive regeneration. These devices have been found to achieve 95% efficiency for control of PM emissions with 3 ppm sulfur fuel.[12] Efficiency dropped to zero with 150 ppm sulfur fuel, and PM emissions more than doubled over the baseline with 350 ppm sulfur fuel. PM increases mostly from water binding to sulfuric acid. Soot emissions also increase with higher sulfur fuel. However, even with the 350 ppm sulfur fuel, diesel particulate filters maintain around 50% efficiency for non-sulfate PM. The systems eventually recover their original PM control efficiency when near-zero sulfur fuels are used again, but recovery takes time because of sulfate storage on the catalyst.

75. As noted in a recent study by The Energy and Resource Institute (TERI) of PM filters and low sulfur fuel in Mumbai, “Continuously Regenerating Technology (CRT™) proved to be highly effective in reducing PM emissions" from buses meeting the Bharat Standard II

[12] US Department of Energy (DOE). 1999. Diesel Emission Control—Sulfur Effects (DECSE). Washington, DC, US DOE

(equivalent to Euro 2) when powered with ultra low sulfur diesel (ULSD).[13] It is important, however, to highlight that this technology is very sensitive to the sulfur content in diesel. According to Johnson Matthey, its manufacturer, it can work effectively only if used in a modern diesel bus running on not more than 50 ppm sulfur diesel or ULSD. The technology's conversion efficiency, after it was stabilized, was found to be 95% for soluble organic fraction and over 98% for insoluble organic fraction. It also was very effective in reducing the free acceleration smoke.

76. Sulfur also increases the temperature required for filter regeneration. In moving from 3 to 30 ppm sulfur fuel, the exhaust temperatures required for regeneration increase by roughly 25°C. The catalyzed diesel particulate filter requires consistently higher temperatures but holds stable above 30 ppm, while the continuously regenerating diesel particulate filter requires ever-increasing temperatures.

77. Work continues to develop filters that are less sensitive to sulfur in fuels. One emerging technology, the so-called flow through filter that achieves about 50% PM reduction, is less sensitive to sulfur than the wall flow filter, which can achieve 90% or greater PM reductions. Data are currently not sufficient to determine if such systems can perform reliably for extended mileage using fuels with more than 50 ppm sulfur.[14]

c. NO_X Control Systems

78. Many diesel engines rely on injection timing retard to meet current NO_X standards. Injection timing retard reduces the peak temperature and pressure of combustion, thus reducing NO_X formation. Unfortunately, this solution both increases PM emissions and significantly decreases fuel economy. For example, NO_X emissions can be decreased by 45% by retarding the injection timing eight degrees, but this change reduces fuel economy by 7%. Injection timing retard is not affected by sulfur in fuel.

79. EGR, another NO_X control strategy used extensively today, is only indirectly affected by fuel sulfur. Two very different technologies—NO_X adsorbers and SCR systems—are the most likely alternatives for stringent NO_X control.

i. Exhaust Gas Recirculation

80. Major advances in diesel NO_X control have been made with EGR, which lowers combustion temperatures and thus reduces thermal NO_X formation. Fuel sulfur does not impact emissions from EGR systems in diesel engines, but it does decrease system durability and reliability due to sulfuric acid formation. For EGR to be effective, the exhaust gases must be cooled, which causes sulfuric acid to condense in the recirculation system. Acid formation raises system costs because premium components and increased maintenance are required.

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[13] The Energy and Resources Institute (TERI). 2004. *Workstream 1: Evaluation of Alternative Fuels and Technologies for Buses in Mumbai, Final Report* [TERI Project Report No. 2001UT41]. New Delhi: TERI

[14] A retrofit demonstration project is underway in Beijing in which such systems will be run with some higher sulfur level fuels to see if they will be able to perform adequately.

ii. Selective Catalytic Reduction

81. SCR is emerging as the leading NO_X reduction technology in Europe to meet Euro 4 and Euro 5 heavy-duty diesel standards. SCR injects urea as a reducing agent into the exhaust gas before the catalyst to achieve high rates of NO_X conversion in the oxygen-rich exhaust. SCR systems are completely ineffective if the urea reagent is not added. Thus, in-use enforcement and monitoring are critical when this technology is used. European regulators are taking steps to require fail safe systems that will significantly degrade vehicle performance if the urea tank is not filled. SCR systems for stationary systems have over 90% conversion efficiency and are widely used for diesel generators and power production.

82. Sulfur does not reduce conversion efficiency in SCR systems as directly as in other advanced control technologies, but it does affect emissions. First, fuel sulfur increases PM emissions from the downstream oxidation catalyst. Second, sulfur reactions in urea-based SCR systems can also form ammonium bi-sulfate, a severe respiratory irritant.

iii. NO_X Adsorbers

83. NO_X adsorbers—also known as NO_X storage catalysts or lean NO_X traps—were introduced in 2007 in the United States for some engines. They have demonstrated 95% efficiency in conversion of NO_X to diatomic nitrogen, with a nominal fuel penalty of 1.5%. However, without significant technological breakthroughs, it is generally recognized that this system can only operate with near zero sulfur fuels.

d. PM Retrofits

84. Data increasingly show that the combination of very low sulfur fuel (usually 50 ppm sulfur or less) and particulate filters can reduce PM approximately 90% and further substantially reduce CO and HC from existing diesel vehicles, even after 640,000 kilometers (km) of operation.[15] The TERI study cited earlier (footnote 13) showed similar reductions on a small fleet in India. To obtain these reductions, however, the technology must be matched carefully to the vehicles, with special attention given to operational patterns and exhaust temperature profiles. Demonstration projects are underway in Bangkok, Beijing, and Pune to determine if such systems can perform satisfactorily under Asian conditions.

85. Diesel oxidation catalysts can also be retrofitted to existing diesel vehicles, as in Hong Kong, China with overall PM reduction on the order of 25%.

6. Conclusions Regarding Diesel Fuel

86. As a general rule, countries following the progression of Euro vehicle standards should adopt the Euro vehicle fuel standards. From the standpoint of emission control technology, the most important diesel parameter is the sulfur content of the fuel. Once Euro 2 standards are introduced, the sulfur content should be reduced to a maximum of 500 ppm. For Euro 3, the maximum sulfur content should be 350 ppm, while the maximum should be 50 ppm for Euro 4. If sulfur exceeds these levels, pollution control systems will not perform optimally, and in-use

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[15] Schaefer, Bob. 2003. *The Success of Diesel Retrofits: A Fuel Supplier Perspective*. BP Global Fuels Technology. Available: http://www.epa.gov/air/caaac/mstrs/schaefer_1203.pdf

emissions will likely exceed standards. Depending on the technology selected by the vehicle manufacturer, permanent damage could occur from the use of higher sulfur fuels in vehicles meeting Euro 4 and higher standards.

C. Gasoline Vehicles and Fuels

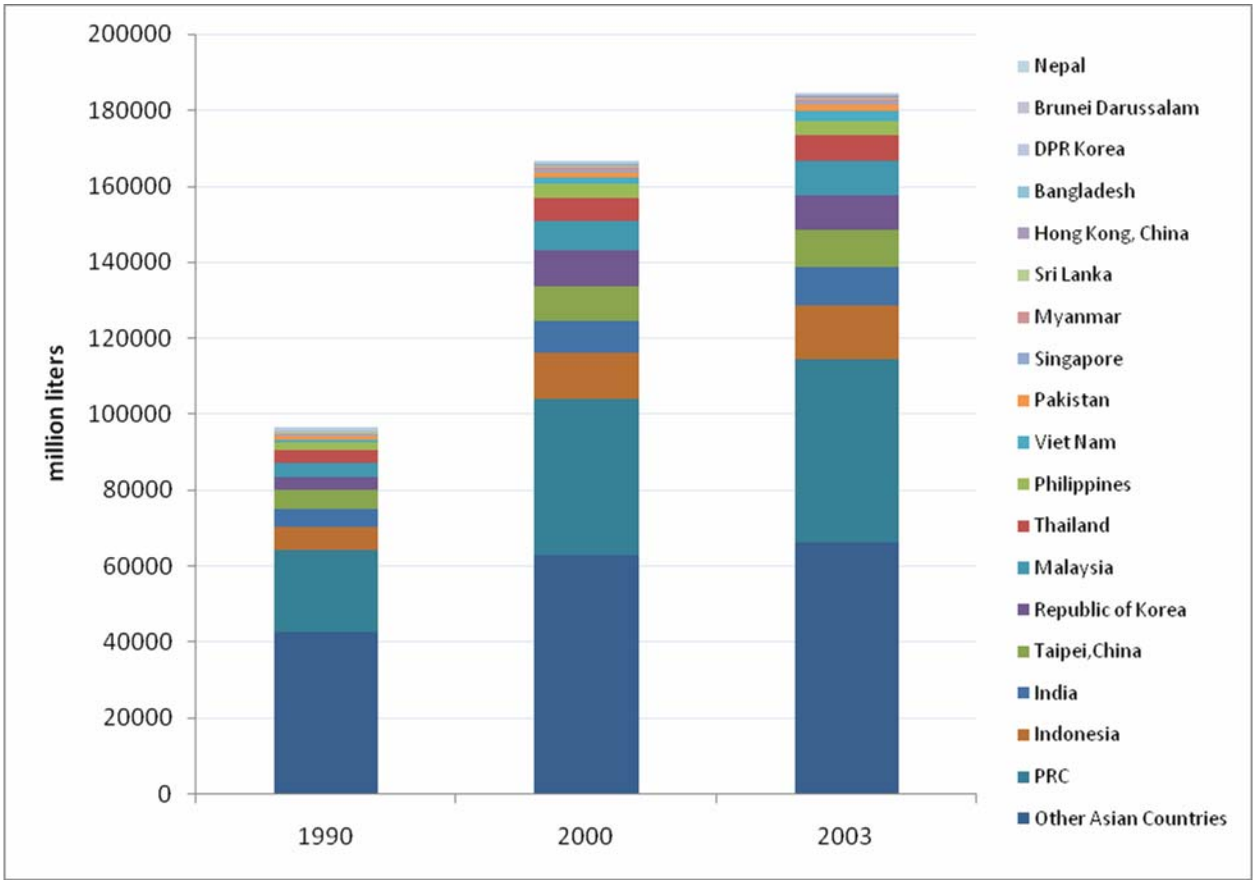
1. Trends with Respect to Gasoline Vehicle Fleet Composition in Asia

87. Although the percentage of diesel fueled passenger cars in some Asian countries is increasing, most passenger cars in Asia remain gasoline-fueled. Two unique characteristics of the gasoline-fueled fleet in Asia are that it is the fastest growing in the world by far (Figure 2.3) and it dominates the global market for two- and three-wheeled motorcycles and scooters.

2. General Description of Gasoline Fuel Parameters

88. Gasoline is a complex mixture of volatile hydrocarbons used as a fuel in internal combustion engines. The pollutants of greatest concern from gasoline-fueled vehicles are CO, HC, NO_X, lead, and certain toxic HC such as benzene. Each of these can be influenced by the composition of the gasoline used by the vehicle. The characteristics of gasoline with the greatest effect on emissions are lead content, sulfur concentration, volatility, aromatics, olefins, oxygenates, and benzene level.

Figure 2.3: Annual Gasoline Consumption Trends in Asia
(in million liters)



DPR Korea = Democratic People's Republic of Korea, PRC = People's Republic of China.
Source: International Energy Agency Statistics Division. 2006. *Energy Balances of OECD Countries (2006 edition)--Extended Balances and Energy Balances of Non-OECD Countries (2006 edition)--Extended Balances*. Paris: IEA. Available: http://data.iea.org/ieastore/default.asp

3. Impact of Gasoline Composition on Asian Vehicle Emissions

89. Table 2.5 summarizes the impacts of various gasoline fuel qualities on emissions from light-duty gasoline vehicles.

Table 2.5: Impact of Gasoline Composition on Emissions from Light-Duty Vehicles[a]

Gasoline	No Catalyst	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5[b]	Comments
Lead↑	Pb, HC↑	CO, HC, NO_X all increase dramatically as catalyst destroyed					
Sulfur↑ (50 to 450 ppm)	SO_2↑	CO, HC, NO_X all increase ~ 15–20% SO_2 and SO_3 increase					Onboard diagnostic light may come on incorrectly
Olefins↑	Increased 1,3 butadiene, increased HC reactivity, and NO_X, small increases in HC for Euro 3 and cleaner						Potential deposit buildup
Aromatics↑	Increased benzene in exhaust						Deposits on intake valves and combustion chamber tend to increase
	potential increases in HC, NO_X	HC↑, NO_X↓, CO↑		HC, NO_X, CO ↑			
Benzene↑	Increased benzene exhaust and evaporative emissions						
Distillation Characteristics T50, T90↑	Probably HC↑	HC↑					
RVP↑	Increased evaporative HC Emissions						Most critical parameter for Asian countries because of high ambient temperatures
Deposit control additives↑		Potential HC, NO_X emissions benefits					Help to reduce deposits on fuel injectors, carburetors, intake valves, combustion chamber

CO = carbon monoxide, HC = hydrocarbons, NO_X = nitrogen oxides, O_2 = oxygen, Pb = lead, ppm = parts per million, RVP = Reid vapor pressure, SO_2 = sulfur dioxide, SO_3 = sulfur trioxide, T50 = temperature at which 50% of the gasoline distills, T90 = temperature at which 90% of the gasoline distills.

[a] The impacts of additives which increase the octane rating of gasoline are described in chapter 4.

[b] Euro 5 emission standards were recently adopted for implementation in 2009; Euro 6 was also adopted for 2014 implementation.

Source (for note b only): European Union. 2007. *Euro 5 and Euro 6 Standards: Reduction of Pollutant Emissions from Light Vehicles. Regulation (EC) No715/2007*. Strasbourg. Available: http://europa.eu/scadplus/leg/en/lvb/l28186.htm

4. Two- and Three-Wheeled Vehicles

90. Asia has a higher proportion of two- and three-wheeled vehicles than elsewhere in the world. Although emissions from these vehicles are expected to be influenced by fuel characteristics, there has been very little study of the impacts of specific fuel parameters on these vehicles. In Table 2.6, these impacts are estimated from the limited available data and the combustion similarities between these and other internal combustion engines.

Table 2.6: Impact of Gasoline Composition on Emissions from Motorcycles[a]

Gasoline	No Catalyst	India 2005	Euro 3	India 2008	Taipei,China Stage 4	Comments
Lead↑	Pb, HC↑	CO, HC, NO_X↑ dramatically as catalyst destroyed				
Sulfur↑ (50 to 450 ppm)	SO_2↑	CO, HC, NO_X↑; SO_2 and SO_3↑				
Olefins↑	1,3 butadiene, HC reactivity, and NO_X↑					Potential deposit buildup
Aromatics↑	Benzene exhaust↑					
Benzene↑	Benzene exhaust and evaporative emissions↑					
Distillation characteristics T50, T90↑	Probably HC↑	HC↑				Not as quantifiable as in passenger cars
RVP↑	Evaporative HC Emissions↑					
Deposit control additives↑		Potential emissions benefits				Help to reduce deposits on fuel injectors, carburetors

CO = carbon monoxide, HC = hydrocarbons, NO_X = nitrogen oxides, O_2 = oxygen, Pb = lead, ppm = parts per million, RVP = Reid vapor pressure, SO_2 = sulfur dioxide, SO_3 = sulfur trioxide, T50 = temperature at which 50% of the gasoline distills, T90 = temperature at which 90% of the gasoline distills.
[a] The impacts of additives which increase the octane rating of gasoline are described in chapter 4.
Source: Authors

91. Most two- and three-wheeled vehicles in Asia are not equipped with catalytic converters to control emissions. It would seem therefore that the impact of the various fuels parameters will be similar as to those on pre-Euro 1 cars. Some catalysts are starting to enter the fleet as emission standards are being tightened, especially in India, Taipei,China, and Europe. These vehicles are anticipated to be affected by sulfur and lead in a manner similar to Euro 1 and 2 gasoline fueled cars. For two- and three-wheeled vehicles equipped with two-stroke engines, the amount and quality of the lubricating oil is probably more important for emissions than is fuel quality.

5. Changes in Gasoline Fuel Parameters in Asia to Achieve Lower Emissions

92. The use of catalyst exhaust gas treatment required the elimination of lead from gasoline. This change, which has occurred throughout most of Asia, has dramatically reduced ambient lead levels. Other gasoline properties that can be adjusted to reduce emissions include, in approximate order of effectiveness, sulfur level, vapor pressure, distillation characteristics, light olefin content, and aromatic content.[16]

93. As a general rule, countries following European vehicle emission standards should be guided by the equivalent fuel quality standards. This is especially true for lead and sulfur, as these fuel parameters are closely linked to the technologies used to comply with the vehicle emission standards.

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[16] Sawyer, R. F. 1993. Reformulated Gasoline for Automotive Emissions Reduction. In *Twenty-Fourth Symposium (International) on Combustion*, 1423–32. Pittsburgh: The Combustion Institute.

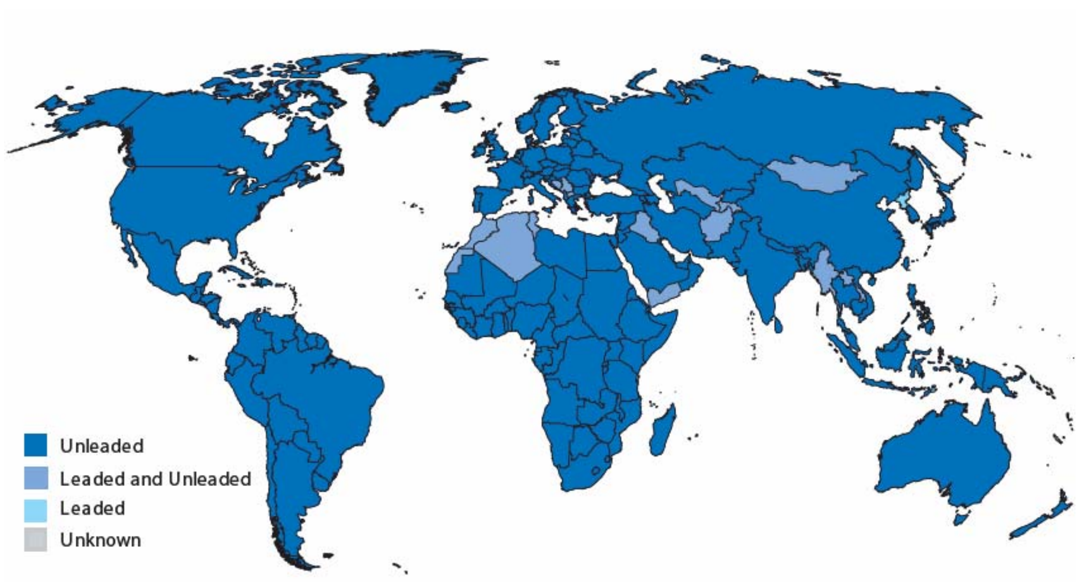
a. Lead

94. Lead additives have been blended with gasoline since the 1920s, primarily to boost octane levels. Lead is not a natural constituent of gasoline; it is added during the refining process as either tetramethyl lead (TML) or tetraethyl lead (TEL). In addition to increasing the octane level of gasoline, lead also lubricates the engine valves and valve seat interface of vehicles that have soft valve seats, thereby minimizing wear.

95. Vehicles using leaded gasoline cannot use a catalytic converter, and thus have much higher levels of CO, HC, and NO_X emissions. In addition, lead itself is toxic and has long been recognized as a serious health risk. Absorbed after being inhaled or ingested, lead can cause a wide range of biological harm depending on the level and duration of exposure. Children, especially those under the age of four, are more susceptible to these effects than adults.

96. The worldwide map in Figure 2.4 shows that almost every country in the Asia-Pacific region has eliminated leaded gasoline.

Figure 2.4: Lead Free Gasoline Worldwide, 2008



Source: UNEP Partnership for Cleaner Fuels and Vehicles. Available: www.unep.org/pcfv/PDF/ MapWorldLead-Jan2008.pdf

b. Sulfur

97. Sulfur occurs naturally in crude oil. The level of sulfur in refined gasoline depends upon the source of the crude oil used and the extent to which the sulfur is removed during the refining process.

98. Sulfur in gasoline reduces the efficiency of catalysts that are designed to limit vehicle emissions and impairs heated exhaust gas oxygen sensors. High sulfur gasoline impedes the introduction of new lean burn technologies using De-NO_X catalysts. Low sulfur gasoline will enable new and future conventional vehicle technologies to realize their full benefits, especially as existing vehicles equipped with catalysts will generally have improved emissions. Phosphorus introduced in additives such as detergents can also act as a catalyst poison. As this effect is well known, the addition of compounds containing phosphorus to gasoline is prohibited under European standard EN228 and similar standards elsewhere (e.g., in Kenya, KS275:2005), and by limits in the United States (0.0013 grams/liter phosphorus), Australia, and other countries.

99. Laboratory testing of catalysts has shown that higher sulfur levels reduce efficiency across a full range of air/fuel ratios. The reduction is higher for low-emission vehicles than for traditional vehicles. Studies have also shown that sulfur hampers the operation of heated exhaust gas oxygen sensors; slows the lean-to-rich transition, thereby introducing an unintended rich bias into the emission calibration; and may affect the durability of advanced on-board diagnostic (OBD) systems.

100. The EPEFE study demonstrated the relationship between reduced gasoline sulfur levels and reduced vehicle emissions of HC, CO, and NO_X. The effects were generally linear, with about 8%–10% reductions as fuel sulfur is reduced from 382 ppm to 18 ppm. The study found that the effects tended to be larger over higher speed driving than in low speed driving. The study also confirmed that fuel sulfur affects catalyst efficiency, with the greatest effect occurring in the warmed-up mode. With regard to air toxins, benzene and C3-12 alkanes (hydrocarbons with 3 to 12 carbon atoms) were in line with overall hydrocarbon reductions, with larger reductions (around 18%) for methane and ethane.

101. The combustion of sulfur produces SO_2, an acidic irritant that also leads to acid rain and the formation of sulfate PM.

102. The Euro 3 and 4 gasoline specifications set maximum sulfur content limits of 150 ppm and 50 ppm, respectively. By comparison, Euro 2 limits were 500 ppm. Subsequently, these limits were tightened to require 10 ppm sulfur fuel to be made widely available in each member country by 2005, and that all gasoline meet these Euro 5 limits by 2009. Several EU countries, including Germany and Sweden, already provide fuels meeting these limits.

c. Vapor Pressure

103. Gasoline volatility indicates how readily a fuel evaporates and is characterized by two measures: vapor pressure and distillation.

104. Reid vapor pressure (RVP) is a measure of the volatility of gasoline in kPa at 37.8°C and is largely determined by the fuel's butane content, whose average RVP is about 350 kPa. Butane content is partly a function of the crude but occurs mostly as a result of refining. Pentanes, with an RVP of about 17 kPa, add volatility to a lesser extent.

105. Sufficiently volatile gasoline is critical to the operation and performance of spark ignition engines. At lower temperatures, higher vapor pressure is necessary for easier start and warm up performance. Control of vapor pressure at high temperatures reduces the likelihood of hot fuel handling problems such as vapor lock and carbon canister overloading. Vapor lock occurs

when too much vapor forms in the fuel lines and fuel flow to the engine decreases, resulting in loss of power and rough engine operation or engine stalls.

106. High gasoline vapor pressure elevates evaporative emissions from motor vehicles and is therefore a priority fuel quality issue. Evaporative emissions may constitute a large part of total hydrocarbon emissions. Fuel may evaporate during the delivery and transfer of gasoline to storage, during vehicle refueling, in the diurnal breathing of vehicle fuel tanks (as they heat up and cool down with normal daily temperature variations), and in the fugitive losses that occur from carburetor and other equipment during normal vehicle operation. Reductions in fuel volatility will significantly reduce evaporative emissions from vehicles. A reduction in vapor pressure is one of the more cost-effective of the fuel-related approaches available for reducing hydrocarbon emissions.

107. Vapor pressure is most effectively managed on a regional and seasonal basis to allow for the different volatility needs of gasoline at different temperatures. Evaporative emissions are effectively reduced if RVP is controlled when ambient temperatures are high, as during the summer.

108. Euro 3 gasoline specifications identify eight volatility classes, each of which is based on seasonal temperature variations and specifies a range of RVP values. Class 1 is the most stringent, with the lowest RVP values for the warmest climates. Classes 7 and 8 pertain to very cold conditions requiring more volatile gasoline blends. The specifications also set a maximum summer (May to September) limit of 60 kPa. For EU countries with arctic conditions, summer runs from 1 June to 31 August, and the RVP is set at 70 kPa. In the United States, especially in California where hot ambient conditions are prevalent, US EPA and the California Air Resources Board (CARB) have set RVP levels close to 50 kPa. In Asian countries, where summer conditions are experienced throughout the year, low RVP limits are critical. In one study for Thailand, reducing the RVP by 6.89 kPa was estimated to result in HC emission reductions of more than 100 tons per day.

d. Distillation

109. Distillation is the second means of measuring the volatility of gasoline. Distillation can be assessed in terms of "T" points or "E" points. For instance, T50 is the temperature at which 50% of the gasoline distills, while E100 is the percentage of gasoline distilled ("E" = evaporated) at 100°C.

110. An excessively high T50 point (low volatility) can worsen starting performance at moderate ambient temperatures. The driveability index, which is derived from T10, T50, and T90 and oxygenate content, can be used as a control to facilitate cold start and warm-up performance. Use of a driveability index also helps to avoid inclusion of a high proportion of high density, poor burning compounds that contribute to CO and NO_X emissions.

111. The EPEFE study found that increasing E100 in gasoline reduces emissions of HC but increases NO_X emissions. At E100, CO emissions were at their lowest value of 50% by volume, for constant aromatics. Increasing E100 from 35% to 50% by volume led to a decrease in mass emissions of both formaldehyde and acetaldehyde. However, increasing E100 from 50% to 65% by volume showed no clear effect.

112. Limiting distillation temperatures and aromatic content appear to be the best means of controlling emissions during the vehicle’s "cold cycle." Heavy end limits (and total aromatic limits)

are the best way to limit heavy aromatics, which is important in managing HC and benzene emissions.

113. Research shows that the formation of deposits in the combustion chamber is related to the heavy hydrocarbon molecules found, among other places, in the T90 final boiling points portion of the gasoline. Reducing deposits in the combustion chamber significantly reduces NO_X emissions.

114. The Euro 3 gasoline specification addresses distillation in terms of two E points: E100 (46% by volume minimum) and E150 (75% by volume minimum), and in terms of a final boiling point of 210°C by volume maximum.

e. Olefins

115. The specific hydrocarbons in gasoline has received more attention in recent years. Given the significant role that hydrocarbon based vehicle emissions play in urban ozone (or photochemical smog) formation and the significant public health hazards from exposure to certain hydrocarbons, there has been a move toward limiting the different hydrocarbon fractions within gasoline, especially the aromatics and the olefins.

116. An olefin is a family of chemicals containing carbon-to-carbon double bonds. Olefins are unsaturated hydrocarbons (such as propylene and butylenes) and, in many cases, are also good octane components of gasoline. They can, however, create engine deposits and increase emissions of highly reactive ozone-forming hydrocarbons and toxic compounds. Also, they tend to be chemically more reactive than other hydrocarbon types.

117. Olefins are easily oxidized and thermally unstable, and they may lead to gum formation and deposits on the fuel injectors and in the engine's intake system. Combustion chamber deposits form from the heavy hydrocarbon molecules found in the olefin portion of gasoline, among other places. Combustion chamber deposits can increase tailpipe emissions, including emissions of CO, HC, and NO_X.

118. Emission of olefins into the atmosphere as chemically reactive species contributes to ozone formation and toxic dienes, which are olefins with two carbon-to-carbon double bonds. The US auto/oil program concluded that reducing total olefins from 20% to 5% would significantly decrease ozone-forming potential. Reduction of low molecular weight olefins accounts for about 70% of the ozone reduction effect. The ozone formation potential of olefins predominantly derives from the lighter volatile olefin fractions, which are typically removed where reductions in low levels of RVP at 48–50 kPa are required. In addition, 1,3-butadiene, a known carcinogen, is formed during the combustion of olefin compounds in gasoline.

119. The EU fuel specifications for Euro 3 set a maximum olefin content of 18% by volume; in 2009 this will be lowered to 13% under the Euro 5 fuel specifications.

120. Under both phases of the US reformulated gasoline (RFG) program, the olefin specification is a maximum 8.5% by volume. The California RFG program (effective since 1996) provides several compliance options for meeting the refiner limits for olefins, including utilizing a maximum (flat) limit of 6% by volume or an averaging limit of 4% by volume coupled with a cap of 10% by volume.

f. Aromatics

121. Aromatics are hydrocarbon fuel molecules based on the six-carbon benzene ring series or related organic groups, and contain at least one benzene ring. Benzene (discussed separately below), toluene, ethylbenzene, and xylene are the principal aromatics, and they represent one of the heaviest fractions in gasoline. Lower levels of aromatics enable a reduction in earlier catalyst light-off time—the temperature at which catalytic conversion can take place—for all vehicles.

122. Research indicates that combustion chamber deposits can form from the heavier hydrocarbon molecules found in the aromatic hydrocarbon portion of gasoline. These deposits can increase tailpipe emissions, including CO_2, HC, and NO_X.

123. The aromatic content of gasoline has a direct effect on tailpipe CO_2 emissions. The EPEFE study demonstrated a linear relationship between CO_2 emissions and aromatic content. A reduction of aromatics from 50% to 20% was found to decrease CO_2 emissions by 5%. This is thought to be due to the effect of aromatics on the hydrocarbon ratio and, hence, the carbon content of the gasoline. No clear effect of aromatics was found on calculated fuel consumption.

124. The EPEFE study also found that changes in emissions result from changes to the aromatic content of fuel and from other parameters such as distillation. Reducing the aromatic content of gasoline also contributes to the reduction of NO_X.

125. A number of countries have set maximum aromatic content limits by volume. Euro 3 and Euro 4 limits are 42% and 35% by volume, respectively. The US specifications under the RFG program were 27% in phase 1 (January 1995) and have been 25% in phase 2, beginning in January 2000. California set separate specifications under its RFG program: 32% in phase 1 (January 1992), and 22% in phase 2 (January 1996). In Japan, the specifications for regular and premium grades set maximum aromatic content levels at 42% by volume. In the Republic of Korea they were set as maximum limits by volume at 45% in 1998, reducing to 35% in January 2000.

g. Benzene

126. Benzene is a six-carbon, colorless, clear liquid aromatic that occurs naturally in gasoline, and that is also a product of catalytic reforming used to boost octane levels. A fairly stable chemical, it is highly volatile and has a high octane rating (research octane number 106, motor octane number [MON] 103).

127. Benzene in gasoline is emitted through both evaporation and exhaust. The EPEFE study found that benzene exhaust emissions varied between 3.6% and 7.65% of total volatile organic compounds from gasoline containing benzene of 1.7% to 2.8% by volume.

128. Combustion of aromatics can lead to the formation of toxic benzene in exhaust gas. Benzene is a proven human carcinogen that can cause leukemia in humans. Approximately 50% of the benzene produced in the exhaust is estimated to result from the decomposition of aromatic hydrocarbons in the fuel. Both the auto/oil air quality improvement research program and EPEFE studies showed that lowering aromatic levels in gasoline significantly reduces toxic benzene emissions from vehicle exhaust. In the EPEFE study, benzene emissions were found to vary between 3.6% and 7.65% of total volatile organic compounds for fuel aromatic contents

ranging from 19.5% to 51.1% by volume. This is consistent with previous studies and can be explained by the de-alkylation of substituted aromatics.

129. Regulators have determined that controlling benzene levels in gasoline is the most direct way to limit its evaporative and exhaust emission and the risks arising from human exposure to it. As a result, over the last decade regulators have been steadily lowering the benzene content of gasoline. The Euro 3 and 4 gasoline specifications set maximum benzene limits of 1% by volume. This compares with the Euro 2 limit of 5%. The United States set a flat limit of 0.8% benzene by volume under the RFG program beginning in January 1995. It has recently adopted a national cap on benzene limits similar to those on reformulated gasoline. Japan introduced a maximum limit of 5% benzene by volume in 1996, which was reduced to 1% in 2000. In Singapore the current limit is 4%, and in Thailand it is 3.5% for all gasoline grades with a future target of 1%.

6. Engine Technology and Emission Control Technologies for Four-Wheeled Gasoline Vehicles

130. Modern gasoline engines use computer controlled intake port fuel injection with feedback control based on an oxygen sensor to meter precisely the quantity and timing of fuel delivered to the engine. Control of in-cylinder mixing and use of high-energy ignition promote nearly complete combustion. The three-way catalyst provides greater than 90% reduction in the emissions of CO_2, HC, and NO_X. Designs for rapid warm-up minimize cold-start emissions. OBD systems sense emission systems performance and identify component failures. Durability in excess of 160,000 kilometers, with minimal maintenance, is now common.

131. The use of catalyst exhaust gas treatment required the elimination of lead from gasoline. Other gasoline properties that can be adjusted to reduce emissions are, roughly in order of effectiveness, sulfur level, vapor pressure, distillation characteristics, light olefin content, and aromatic content. Of these, sulfur is the most important in terms of the impact on advanced pollution control technology. The impact of sulfur on different technologies is summarized below.

a. No Controls and Pre-Catalyst Controls

132. The amount of sulfur in the fuel is directly related to SO_2 emissions, some of which are converted to sulfate PM in the atmosphere.

133. For gasoline fueled vehicles with no catalytic converters, reducing sulfur will have no effect on the principal pollutants of concern, CO, HC, or NO_X. Although the amount of SO_2 emitted is in direct proportion to the amount of sulfur in the fuel, gasoline vehicles are not usually a significant source of SO_2. Because SO_2 can be converted in the atmosphere to sulfates, however, these emissions will also contribute to ambient levels of PM_{10} and $PM_{2.5,}$ which is frequently a serious concern.

b. Catalyst-based Controls

134. All catalyst technology is degraded by sulfur, which increases CO, HC, and NO_X. Approximately 90% of new gasoline vehicles worldwide are equipped with a three-way catalyst, which simultaneously controls emissions of CO, HC, and NO_X. Sulfur in fuel impacts three-way catalysts functioning in several ways.

c. Fuel Sulfur Reduces Conversion Efficiency for CO, HC, and NO_X

135. Sulfur competes with emissions of CO, HC, and NO_X for reaction space on the catalyst. It is stored by the catalyst during normal driving conditions and released as SO_2 during periods of fuel-rich, high-temperature operation, such as high acceleration. Reducing sulfur levels in gasoline—from highs of 200–600 ppm to lows of 18–50 ppm—has resulted in 9% to 55% reductions in HC and CO emissions and 8% to 77% reductions in NO_X emissions, depending on vehicle technologies and driving conditions. Greater percentage reductions have been demonstrated for low emission vehicles and high-speed driving conditions.

d. Sulfur Inhibition in Catalysts is Not Completely Reversible

136. Although conversion efficiency will always improve with the reintroduction of reduced sulfur fuel, the efficiency of the catalyst is not restored to its original state after desulfurization. In tests using 60 ppm sulfur fuel followed by a single use of 930 ppm sulfur fuel, HC emissions tripled from 0.02 grams per km to 0.07 grams per km. With a return to low sulfur fuel, emissions dropped to 0.4 grams per km, but fuel-rich operation (resulting in high exhaust temperatures) was required to regenerate the catalyst fully and return to original emission levels.

e. Sulfur Content in Fuel Contributes to Catalyst Aging

137. Higher sulfur levels cause more serious degradation over time and, even with elevated exhaust temperatures, less complete recovery of catalyst function. The high temperatures necessary to remove sulfur from the catalyst also contribute to thermal aging of the catalyst. Sulfur raises the light-off temperature resulting in increased cold-start emissions.

f. Regeneration Requirements Add to Overall Emissions and Reduce Fuel Efficiency

138. Fuel-rich operation required to reach regeneration temperatures significantly increases CO and HC emissions, and PM emissions under these circumstances can actually rival diesel emissions. In addition, fuel-rich combustion uses more fuel. Vehicles that tend to operate at low speed and low load will have lower exhaust temperatures, which, by inhibiting catalyst regeneration, will limit the amount of sulfur that can be removed from the catalyst.

g. More Advanced Catalyst Controls

139. All catalyst technology is degraded by sulfur, which increases CO, HC, and NO_X. Some advanced catalyst technologies such as NO_X adsorbers, which may enter the market in the next 10 years, are precluded by high levels of sulfur.

140. The percentage benefits of reducing sulfur levels in fuels increase as vehicles are designed to meet stricter standards. Increasingly strict emission standards require extremely efficient catalysts over a long lifetime. Recent regulations in Europe and the United States require warmed-up catalysts to have over 98% HC control, even towards the end of the vehicle's lifetime (i.e., 100,000 km in Europe and over 160,000 km in the United States).

D. Fuel Quality Monitoring

141. Regardless of the fuel specifications adopted, only routine monitoring at the pump and along the distribution chain can ensure that the actual fuels used meet the specifications. Penalties should be imposed if the limits are not achieved.

142. Because of differences in national fuel taxes and subsidies, special care must be taken in some cases to minimize or eliminate adulteration of high quality fuels with lower quality, cheaper alternatives such as kerosene.

143. A comprehensive fuel adulteration study undertaken in India indicates that extremely weak product quality monitoring stems largely from weak regulations and enforcement, skewed market prices of different petroleum products, and a lack of accountability in the petroleum sector.[17] As this study concludes, unless these conditions are corrected, the root cause of the problem cannot be eliminated. Although there is agreement that skewed prices are largely responsible for adulteration, thus far for political reasons, possible solutions have not been implemented.

144. The study from India also clearly indicates that unless serious steps are taken to prevent and check adulteration, the profitable business of adulteration will continue. The current system is fundamentally compromised by both testing methods that are inadequate to detect adulteration and penalty systems that are too weak to be an effective deterrent.

E. Conclusion

145. One of the most important lessons learned in the approximately 30-year worldwide history of vehicle pollution control is that vehicles and fuels must be treated as a system. Improvements in vehicles and fuels must proceed in parallel if significant improvements in vehicle related air pollution are to occur. A program that focuses on vehicles alone is doomed to fail; conversely, a program designed to improve fuel quality alone will not succeed.

146. A second important lesson is that a program that focuses on cleaning up vehicles and fuels as a system can succeed. Most Asian countries are following the EU system for cleaning up vehicles and fuels, and this system provides a clear road map that carefully links vehicle emission standards and the associated technologies with appropriate fuel parameters and specifications needed to optimize emissions performance. Although deviations from some of the fuel parameters are possible and may even be necessary to account for differences in climate and refinery configurations, this should not include deviations from the specifications for lead or sulfur without very careful study and analysis.

147. Reformulated diesel fuels can effectively reduce NO_X and PM from all diesel vehicles. These fuels have reduced sulfur, reduced aromatics, and increased cetane number. However, certain technologies are especially sensitive to the sulfur content of the fuel. For pre-Euro 2 vehicles, lowering sulfur will tend to lower SO_2 and PM emissions, but is not linked directly to diesel technology. Euro 2 vehicles, however, should have fuel with a maximum of 500 ppm

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[17] Centre for Science and Environment. 2002. *A Report on the Independent Inspection of Fuel Quality at the Fuel Dispensing Stations, Oil Depots and Tank Lorries*. Submitted to the Environmental Pollution (Prevention and Control) Authority. New Delhi.

sulfur; Euro 3 with a maximum of 350 ppm, and Euro 4 with a maximum of 50 ppm. Thus, if stringent control of NO_X and PM were needed, sulfur levels would need to be reduced to 50 ppm or less, and Euro 4 vehicle standards introduced. Technologies to achieve these levels already exist, and even more advanced technologies are being introduced for new vehicles.

148. Experience has also shown that the availability of clean, low sulfur fuel (50 ppm or less) can open up opportunities to substantially reduce emissions from certain fleets of existing vehicles, such as urban buses.

149. Although fuel quality improvements will in most cases be driven by the desire to have cleaner new vehicles entering the fleet, experience has demonstrated the feasibility of aggressively reducing in-use emissions from specific categories of gross polluting vehicles such as city buses.

150. With regard to gasoline fueled vehicles, the use of catalyst exhaust gas treatment requires the elimination of lead from gasoline. This change, which has occurred throughout most of Asia, has resulted in a dramatic reduction of ambient lead levels. Other gasoline properties that can be adjusted to reduce emissions include, in approximate order of effectiveness, sulfur level, vapor pressure, distillation characteristics, light olefin content, and aromatic content (footnote 16). Since catalyst technology is emerging for two- and three-wheeled vehicles, lead free and lower sulfur gasoline will be important for these vehicles as well.

151. Although certain types of retrofit strategies are technically feasible for gasoline fueled vehicles, they have not been as widespread or successful as diesel retrofits and are not likely to be a priority in the region. Retrofit programs are not likely to be undertaken for gasoline fueled vehicles in the years to come in Asian cities.

152. It is worth noting that the Japanese oil industry accelerated the introduction of near zero sulfur levels in both gasoline and diesel at a faster rate than the Government required not only to facilitate the introduction of advanced NO_X and PM controls on vehicles but also to increase the opportunities for more fuel efficient technologies and lower CO_2 emitting technologies to enter the marketplace.[18]

[18] Mikami, Hiroyuki. 2006. E-mail from Hiroyuki Mikami, Japan Petroleum Energy Center (JPEC), to Aurora Ables, CAI-Asia Secretariat, 21 April.

III. PRODUCING CLEAN FUELS IN ASIA

A. Introduction

153. Cleaner gasoline and diesel are fuels with properties that produce less evaporative emissions and that contribute to lower tailpipe emissions from motor vehicles. European and US regulations define clean gasoline and clean diesel as fuels that meet specific standards on eight properties for gasoline and five properties for diesel. Extensive testing programs performed both in the United States and in Europe have identified these properties as influencing emissions from the fuels and from motor vehicles. The severity of the air pollution problems in Europe and the United States over the years has required that regulations specify the acceptable levels for each of these properties in order for the emissions from fuels and motor vehicles to be optimized. Tables 3.1 and 3.2 compare EU standards with US EPA, California, and Japan standards for gasoline and diesel, respectively.

Table 3.1: Comparison of Gasoline Standards for EU, US EPA, California, and Japan

Fuel Property	EU Euro 3	EU Euro 4	US EPA	California	Japan
RVP, kPa		60.0	49.6	48.2	62
Sulfur, ppm	150	50	30	20	50
Aromatic vol %	42	35	25	25	No spec
Benzene vol %	1.0	1.0	1.0	0.8	1.0
Olefins vol %	21/18	18	8.5	6.0	No spec
Oxygen wt %	2.7	–	2.0	2.0	1.2
T90 ^{o}C	–	–	160	152	190
T50 ^{o}C	–	–	99	100	110
E150	75	75	–	–	–
E100	46	46	–	–	–

^{o}C = degrees Celsius, EU = European Union, kPa = kilopascal, ppm = parts per million, no spec = no specifications, RVP = Reid vapor pressure, T50 = temperature at which 50% of the gasoline distills, T90 = temperature at which 90% of the gasoline distills, US EPA = United States Environmental Protection Agency, vol % = percent by volume, wt % = percent by weight.
Note: EU has defined E100, E150 standards.
Source: J. Courtis. 2006.

Table 3.2: Comparison of Diesel Standards for EU, US EPA, California, and Japan

Fuel Property	EU Euro 3	EU Euro 4	US EPA	California	Japan
Sulfur, ppm	350	50	15	15	10
Cetane Number	51	51	50+	50+[a]	45
Cetane Index	46	52	–	–	45
Density, kg/m^3	845	845	–	–	860
Distillation			–	–	
T95 ºC	360	360	–	–	360
PAH, vol %	11	4	–	–	–
Total Aromatic Vol %	–	–	–	10-20+[a]	–

^{o}C = degrees Celsius; EU = European Union; kg/m^3 = kilograms per cubic meter; PAH = polycyclic aromatic hydrocarbon; ppm = parts per million; T95 = temperature at which 95% of the diesel distills; US EPA = United States Environmental Protection Agency; vol% = percent by volume.

[a] Cetane and aromatics are defined through alternative formulation provisions.

Source: J. Courtis. 2006.

154. The comparisons in Tables 3.1 and 3.2 indicate that although there are significant similarities, there are also differences between the Euro 4 standards for both gasoline and diesel fuels and the standards adopted by US EPA and by California, especially for RVP, and levels of sulfur and aromatic compounds. However, the implementation of the Euro 5 fuel standards, followed by the Euro 6 standards, would reduce these differences. It should be noted that some refineries in other parts of the world, especially the Middle East, are gearing up to provide refined products to Asia, and the specifications of those products will depend on the specifications required by Asian countries.

Table 3.3: Fuel Standards for Selected Asian Countries

Fuel Properties	PRC[a]	Hong Kong, China	India	Indonesia	Japan	Republic of Korea	Malaysia	Philippines	Taipei,China	Thailand
Gasoline										
RVP, kPa	60	70	60	70	50-70	70	70	70	70	60
Sulfur, ppm	2,000 500 150 (50)	50	150	1,000	50 (10[b])	100	500	500	50	150
Aromatic vol %	40	35	42	–	35	35	–	35	35	40
Benzene vol %	3.5	1.0	1.0	–	1.0	3.5	5.0	–	5.0	1.0
Olefins vol %	35	18	–	–	18	–	–	–	18	18
Diesel										
Sulfur, ppm	2,000 (500; 50)	50	500 (350[c])	3,500	50 (10[b])	10	500	500	50	150
Cetane Number Minimum	–	51	45	48 & 51	51	–	–	–	51	–

kPa = kilopascal, ppm = parts per million, PRC = People's Republic of China, RVP = Reid vapor pressure, S = sulfur, vol % = percent by volume.
[a] National standard 2,000 ppm, but marketed is 500-1,000 ppm; Beijing 50 ppm in 2008.
[b] National standard is 50 ppm, but industry has voluntarily achieved 10 ppm for diesel (2007) and gasoline (2008).
[c] Various fuel quality available.
Source: (i) J. Courtis. 2006; (ii) State Environment Protection Administration, PRC. 2000. GB 252-2000 "Light Diesel Fuels" national mandatory standard; (iii) Indonesian Ministry of Energy and Mineral Resources, Directorate General of Oil and Gas. 2008. Fuels Policy. Paper presented at JARI Indonesia Roundtable 2008. Jakarta. 14 Feb 2008. Available: http://www.jari.jp/pdf/InRT2008/03MIGAS.pdf

155. As Table 3.3 indicates, the types of fuels that are currently produced in Asia vary widely. In some countries, the fuels produced comply with standards similar to Euro 1. By contrast, in some other countries, the fuels produced have properties very close to the Euro 4 standards. Some countries have announced road maps for the implementation of fuel and motor vehicle standards that identify the implementation of Euro 4 and even Euro 5 standards as the final goals. For all areas that are experiencing severe air quality problems, the Euro 4 standards, followed by the implementation of Euro 5 and Euro 6, appear to be the optimum mid- to long-term fuel strategy. A clear road map approach is needed to link carefully the vehicle emission standards and the associated technologies with the appropriate fuel parameters and specifications that can optimize emissions performance.

B. Implementation of Fuel Standards

156. In Europe, Japan, and the United States, clean fuel standards were implemented in phases over 30 years. This slow implementation was due to the lack of understanding of the effects of some of the fuel properties on motor vehicle emissions, of the severity of the air pollution, and of the health effects of air pollutants. The phased-in implementation has resulted in additional and unnecessary expenses for the refining industry. In some cases, severe

reformulating occurred that increased levels of aromatics and benzene content; both aromatics and benzene later had to be severely reduced. In other cases, initial moderate reductions in sulfur content resulted in refinery modifications that had to be altered again to accommodate more severe reductions in sulfur content. However, the phased implementation did provide ample time for the refining industry to plan and recover some capital expenditures, a vital feature of EU and US approaches. During the intervening time, new developments in fuel processing technology, as well as improvements in the understanding of the production of cleaner fuels helped to reduce both the refinery capital investments and the operating expenditures.

157. The knowledge gained by the experiences in the United States and Europe, both on the impacts of fuel properties on emissions and on the refinery strategies for implementing cleaner fuel standards, will allow Asian countries to implement cleaner fuel standards without the need for a phase-in period. At a minimum, a clearly defined road map can be developed to identify the fuel targets and the associated time schedule. The oil industry needs a clear understanding of the ultimate targets so that an integrated strategy for the implementation of fuel standards can be developed. Some Asian countries may need to include fuel quality targets beyond Euro 4, resulting in lowering sulfur standards to 10–15 ppm. It would benefit the refineries to be informed early of these regulatory intentions as it may help to reduce their overall investment in the long run.

158. No technical or scientific obstacles hinder the implementation of such a road map and no refining issues pose as obstacles to implementing fuel standards:

- (i) The refining technology needed to produce cleaner fuels that meet the Euro 4 and Euro 5 or equivalent standards is well understood and has been implemented in the United States and the EU.
- (ii) Although the Asian marketing and distribution systems pose significant challenges, the fuel blending, fuel distribution, fuel monitoring, and other issues associated with cleaner fuels are well defined, and there is extensive experience with the marketing of cleaner fuels.
- (iii) The costs of the refining technology are well defined, and a variety of available engineering and construction services have experience that could be employed for refinery modifications.
- (iv) Developments in refining technology during the last 10 years would significantly reduce capital costs.
- (v) Tools that could help optimize the refining operations and reduce operating and other costs are available.

C. Status of Refineries and Refining Industry in Asia

159. In 2004, an estimated 264 refineries of varying size and complexity were operating in 16 Asian countries. Table 3.4 summarizes these and indicates some of their process capacities.

Table 3.4: Summary of Asian Refiners by Country and Process Capacity

Country	Number of Refineries	Crude Distillation Capacity (MBPD)	Light Oil Processing (MBPD)	Conversion (MBPD)	Hydro-treating (MBPD)
PRC	155	5,400	247	1,784	433
Japan	35	4,786	858	1,093	4,232
India	17	2,135	51	222	228
Australia	9	954	296	280	434
Indonesia	8	993	109	293	116
Thailand	7	782	82	115	382
Pakistan	7	285	4	80	90
Republic of Korea	6	2,560	237	307	1,017
Malaysia	6	516	94	91	154
Philippines	5	428	67	47	193
Taipei,China	4	975	151	155	511
Singapore	3	1,259	157	164	592
Myanmar	2	57	–	–	–
New Zealand	1	106	28	29	62
Sri Lanka	1	48	5	–	18
Bangladesh	1	33	2	1	2
Viet Nam	–	–	–	–	–

MBPD = thousands of barrels per day, PRC = People's Republic of China.
Source: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

160. Refineries are classified into three general categories according to their level of complexity.

1. Topping Refineries

161. Topping refineries are usually small facilities that rely exclusively on crude oil distillation for producing various distillate components. The "straight run" streams receive very little processing, and the residuum from the distillation process is sold as fuel oil, converted to asphalt, or sold to other refineries that have additional processing capability. The topping refineries do not have any processes such as catalytic cracking, and they may import blending components to meet fuel specifications. The product mix from such refineries is strongly dependent upon the crude used.

162. Topping refineries have very little clean fuels capacity and their flexibility in this regard is limited. Given their small size, the economies of scale do not favor the installation of new process units for the production of clean fuels. Under a competitive market environment, it might be expected that these refineries, when under private ownership, would find it unprofitable to produce cleaner fuels or to invest in capital expenditures in order to modify or expand their

refineries. In a controlled price environment, or when under governmental ownership, they might continue their operations were the prices to allow the recovery of capital and operating expenditures. In a number of Asian countries, where topping refineries represent an important part of fuel production, and where the fuel supply relies in large part on the fuel production from the topping refineries, the issue of clean fuels' availability and supply could force the implementation of governmental subsidies or increase dependence on imports.

2. Hydroskimming Refineries

163. Hydroskimming refineries are usually mid-sized facilities that, in addition to distillation processes, include processes for catalytic reforming of some of the distillation streams. These processes may include hydrotreating or hydrofinishing that help to improve further the quality of the various distillation fractions produced. Hydroskimming refineries are less dependent on crude quality to meet product specifications. Some of these refineries might be able to produce clean fuels. Depending upon the types of crude oils that these facilities run, they might be able to produce gasoline that nearly meets Euro 4 standards. However, their clean diesel capacity is more limited.

164. A large capital investment, when required, would significantly reduce the profit margins of these refineries, and they might choose not to maintain their current level of production of motor vehicle fuels. The capital investments needed and the overall costs per barrel of fuel processed would be higher compared to the costs incurred by complex refineries. It is possible, however, that some of the hydroskimming refineries will be retrofitted to produce cleaner fuels. This will be easier in an environment where prices are controlled and where the price mechanisms allow the recovery of investments. In the United States almost all of the hydroskimming facilities remained operational at the Euro 2 equivalent regulatory standards. When the Euro 3 and Euro 4 equivalent standards took effect, a number of refineries reduced the production of cleaner fuels, while others retrofitted their processes and continued fuels production. This affected the supply of cleaner fuels. Hydroskimming refineries operate in some Asian countries and are able to produce cleaner fuels.

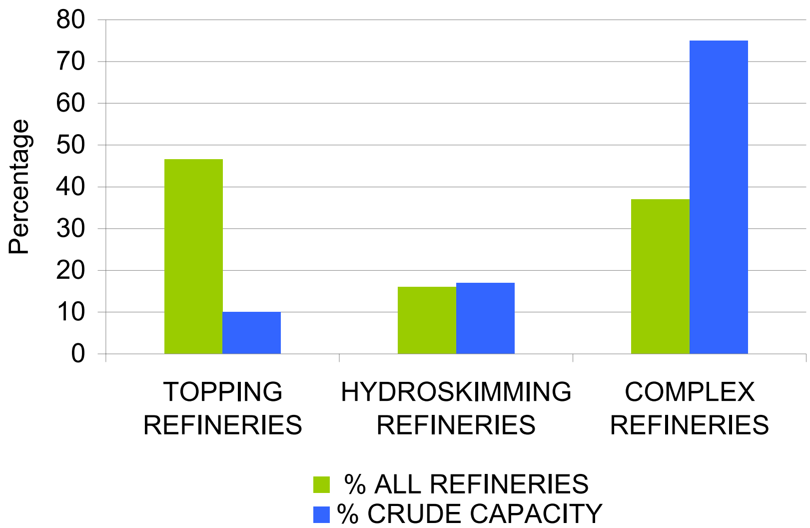
3. Complex Refineries

165. Complex refineries are larger facilities that have a wide range of processing capabilities to alter product yields and quality. In addition to the capabilities of topping and hydroskimming refineries, complex refineries are able to crack fuels, and may have additional processes that produce clean gasoline components such as alkylation, isomerization, and polymerization. These processes can convert low-value residual products to higher value gasoline or diesel, or very light streams into gasoline. Complex refineries may already employ processes that would be useful in the production of clean fuels. However, complex refineries in Asia have a lower concentration of clean gasoline blend-stock plants with processes such as alkylation, isomerization, or hydrotreating than the complex refineries in Europe or the United States. Asian refineries with these processes represent only 2% of crude capacity, compared with 10% and 15% of the crude capacity for comparable refineries in Europe and the United States, respectively. Thus, the production of clean fuels in Asia at the current production levels would require significant additional capital investments and modifications of refinery operations. For example, even when existing hydrotreating units are in place, it may be necessary to retrofit or rebuild them so as to produce fuels with sulfur content lower than 50 ppm. Additional auxiliary units such as hydrogen production units or sulfur treatment units may also be required. Most of the fuels in Asia are produced by complex refineries. Although the simple or hydroskimming

refineries are still a considerable number, they produce a relatively small percentage of all transport fuels in Asia.

166. As Figure 3.1 indicates, 47% of Asian refineries can be classified as topping refineries. However, these process only about 10% of the crude operational capacity. Fifteen percent of the refineries are hydroskimming facilities accounting for approximately 18% of crude processing capacity, while 38% are complex refineries, responsible for about 75% of crude capacity.

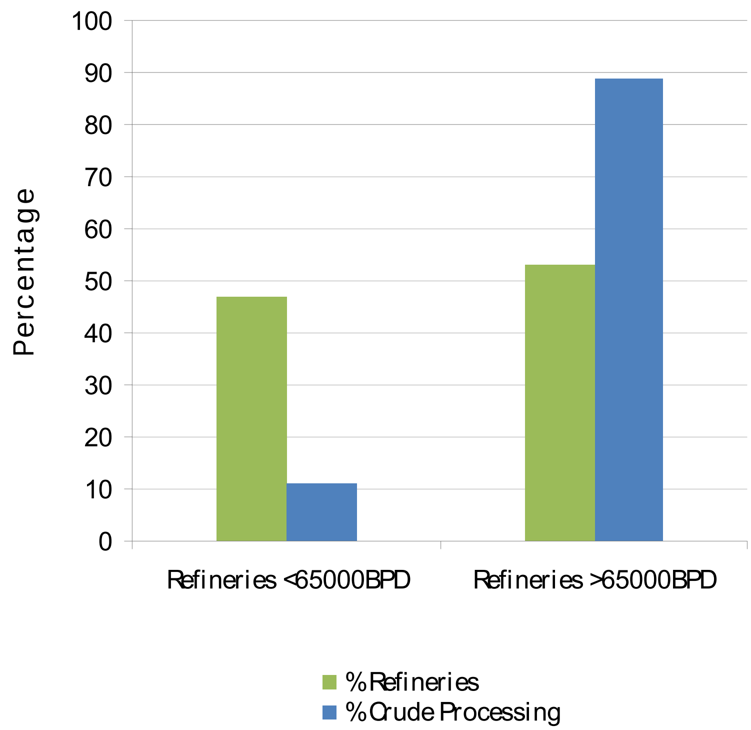
Figure 3.1: Asian Refineries by Category



Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

167. Another measure of the Asian refining industry lies in a comparison of the size of refineries. As a general rule, the 65,000 barrels per day crude throughput separates small refineries from medium or large refineries. Figure 3.2 shows Asian refineries by size and by percent of crude capacity. Approximately 47% of Asian refineries are classified as small, and represent only about 11% of refining capacity.

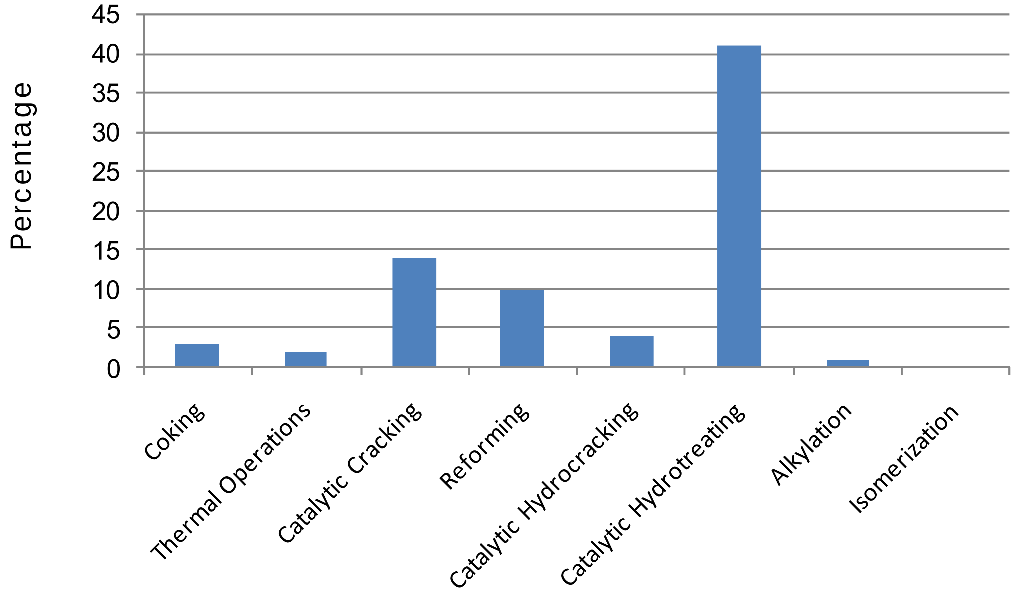
Figure 3.2: Small and Large Asian Refineries by Number and Process Capacity



BPD = barrels per day.
Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

168. Figure 3.3 shows the complexity of refineries in Asia by the type of refinery process and as a percent of crude oil processing capacity. This figure displays low reforming, alkylation, and isomerization capacity, and indicates that capacity to produce cleaner gasoline is limited. The hydrotreating capacity at about 41% of crude capacity is lower than European refineries, suggesting comparatively less capacity to produce low sulfur products in Asia.

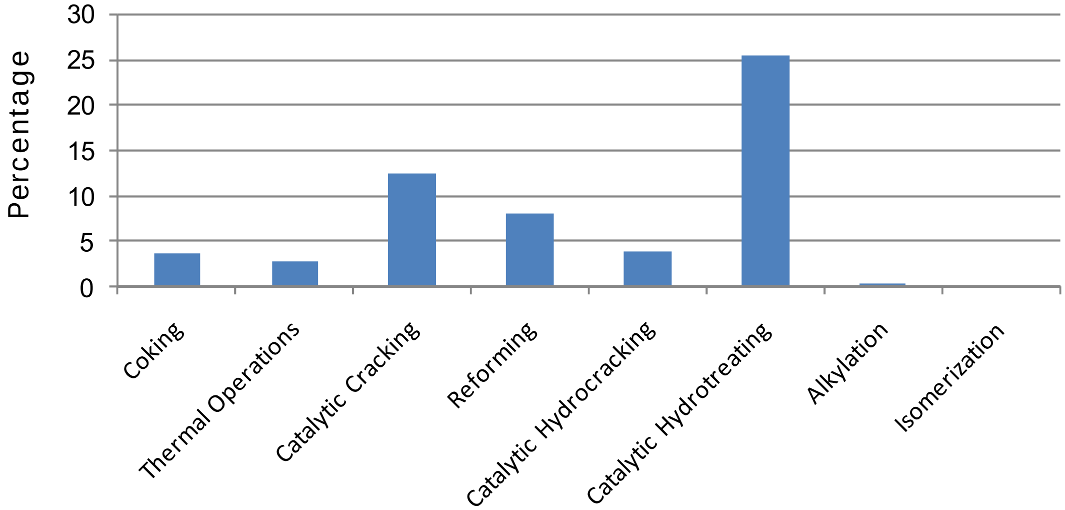
Figure 3.3: Refinery Complexity as a Percent of Crude Capacity in Asia



Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

169. Figure 3.4 highlights the complexity of Asian refineries when Japanese refineries are excluded from the analysis. Under these circumstances, the hydrotreating capacity of Asian refineries is reduced from 41% to 25% of crude distillate capacity. All else being equal, the lower levels of hydrotreating capacity suggest that greater capital investments would be required in Asia than in Europe and the United States to produce low sulfur content fuels. The weaker initial refining industry capabilities in Asia requires careful planning of clean fuels programs in each country in close cooperation with the respective refining industries.

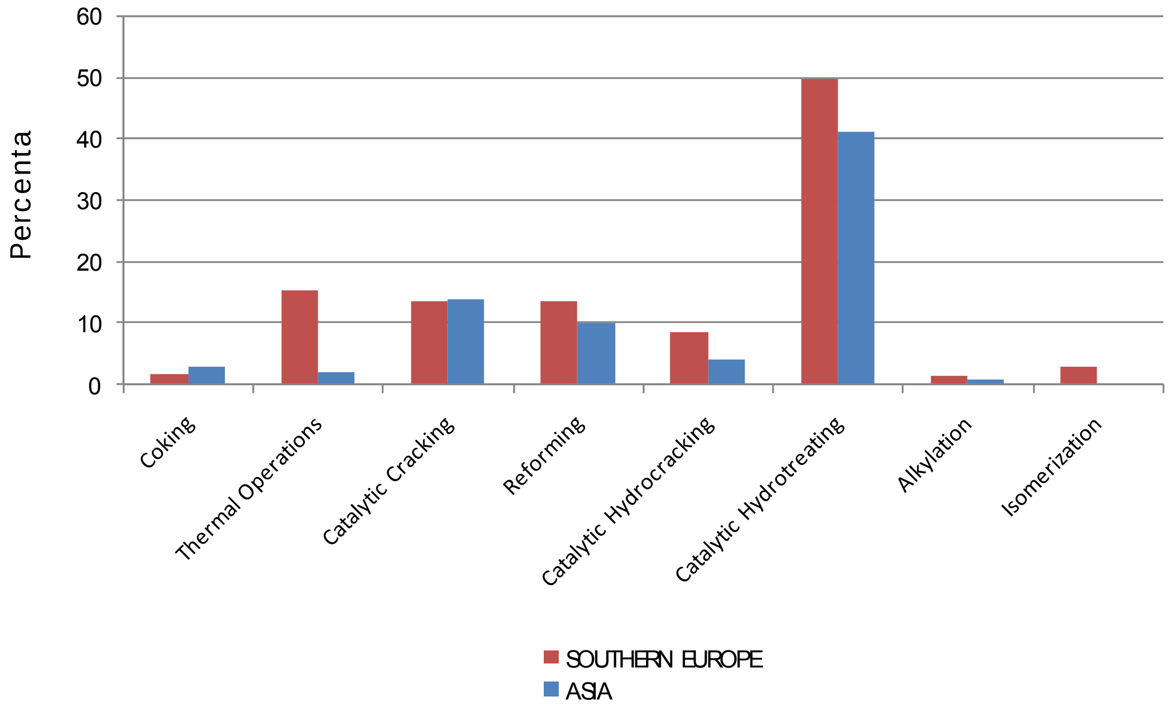
Figure 3.4: Refinery Complexity as a Percent of Crude Capacity in Asia, Excluding Japan



Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

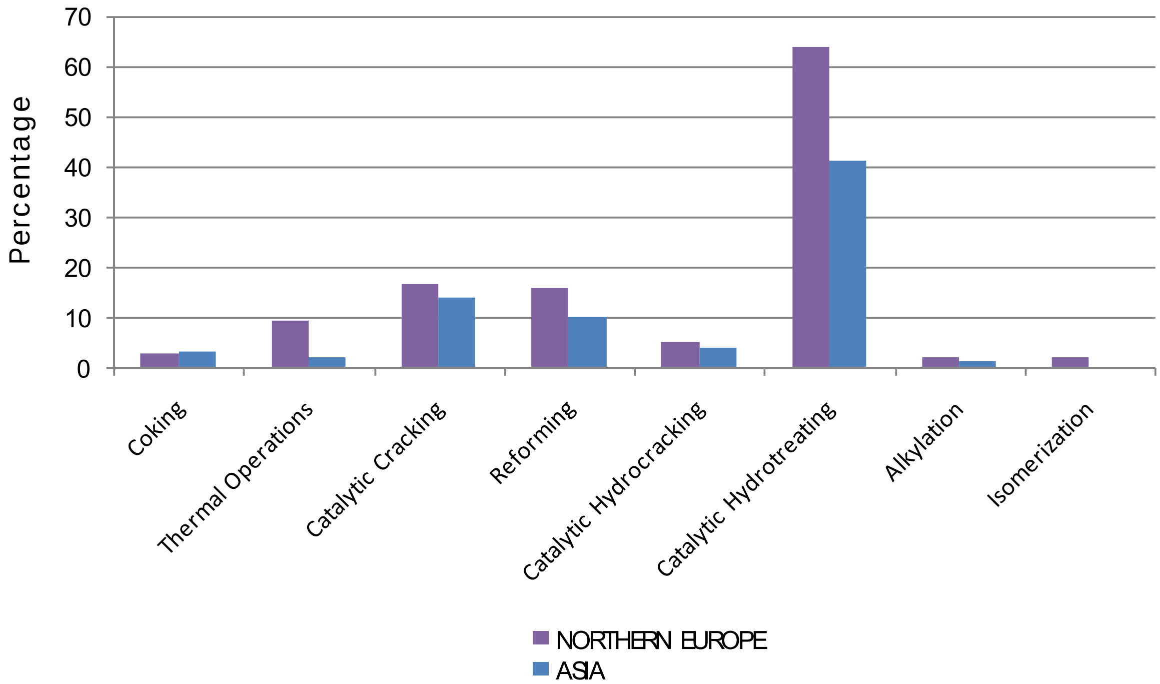
170. Figures 3.5 and 3.6 compare the complexity of Asian refineries with those in southern and northern Europe. The refineries in these three regions seem to emphasize distillate production. Asia's catalytic cracking and hydrocracking capacities represent 14% and 41% of crude capacity, respectively. This compares with 14% and 50% for Southern Europe, respectively, and 17% and 64% for Northern Europe, respectively.

Figure 3.5: Refinery Complexity—Asian vs. Southern European Refineries



Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

Figure 3.6: Refinery Complexity—Asian vs. Northern European Refineries



Source: J. Courtis [Data: (i) Asia-Pacific Economic Cooperation. 2004. *Clean Transportation Fuels Supply Security Study EWG02/2001T, Final Report*. Prepared by HART Downstream Energy Services; (ii) Asian Development Bank. (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Manila: ADB. Prepared by Enstrat International, Ltd. Available: http://www.cleanairnet.org/caiasia/1412/articles-40677_EnstratSulphurReport.pdf

4. Issues with Small Refineries in Asia

171. Small refineries in Asia tend to be older, inefficient facilities that produce small amounts of fuels. They are mostly topping plants, with a few hydroskimming plants. (It should be noted that a number of hydroskimming refineries have a capacity greater than 65,000 barrels per day.) These facilities are not equipped with the process units required to produce a variety of fuels. Some of these small refineries are operated by governmental entities, some are independent, and some are part of a larger and more complex refining system. Considering the system of tariffs and the governmental price controls that exist in some Asian countries, most of these small refineries are protected from market fluctuations and from price uncertainties. The small refineries that are operated by independent or international oil companies tend to be more at risk and in some cases have closed their doors (e.g., refineries in the Philippines and Australia.) To improve efficiency and refinery margins, larger oil companies tend to consolidate operations. Thus, inefficient small facilities are the first to close.

172. For similarly small facilities that were operated in the United States, regulatory agencies considered the possibility that some of the small refineries would close down because of cleaner fuels regulations. As a result of concerns about the effects on fuel supply, the governmental organizations encouraged small refineries' participation in the market and provided special provisions that have delayed the implementation schedule of cleaner fuels or have allowed for

less restrictive, or interim, standards. However, only a small number of these refineries chose to retrofit and to continue the production of motor vehicle fuels. Some refineries discontinued operations, while others have specialized in products for the unregulated markets.

D. Costs of Producing Cleaner Fuels

173. Both non-process and process options can be used for producing cleaner fuels. The non-process options could somewhat improve fuel quality and could supplement or assist the cost reduction when additional process options are considered.

1. Non-process Options

174. Non-process options are operational changes made to the refinery without investments in new process units. The following is an overview of non-process options.

a. Better Quality Crude Oils

175. To the extent that the refinery design allows, a refiner might elect to purchase and process lower sulfur content or better quality crude oils. The produced intermediary streams have lower sulfur content and would be easier to treat. However, such crude oils are more expensive and the resulting gains in quality are limited. Further, while the crude demand increase in many markets has been for light and sweet crude (lower sulfur levels), the majority of new production has been of heavy and sour crude types (higher sulfur levels).

b. Imports and Exchanges

176. A refiner might import better quality blend-stocks such as alkylate, isomerate, or other low sulfur content blending components. However, these products cost more and are scarce. A multi-refinery operator might integrate a multiple refinery system so that each refinery in the system is optimized and some products are exchanged among refineries.

c. Operational Changes

177. A refiner might change the severity and operational characteristics of various processes (cut points, operating pressures, catalysts, etc.) to improve the quality of the products. In addition, a refiner might improve the quality by moving products from the gasoline to the diesel pool or from the diesel to the fuel oil pool.

178. None of these non-process options would require significant capital investments, but they do have design limitations and would have an economic penalty either in the form of additional processing and feedstock costs or as a yield and volume penalty. Refiners might also experience an additional economic penalty due to the downgrading of some products. In general, non-process options are not sufficient by themselves to allow refiners to produce Euro 4 fuels and maintain their fuel production levels.

2. Process Options for Producing Cleaner Fuels

179. Experience from the United States and the EU, as well as results of various studies, indicate that the optimum option would be to build additional equipment, which would require capital investments. The following is a discussion of the various process options for the

production of cleaner gasoline and diesel fuels. To reduce capital and operational expenditures, supplemental non-process options, as described above, could also be implemented.

a. Gasoline

i. Aromatics

180. Aromatics content could be reduced to Euro 4 levels by reducing reformer severity or by blending in the gasoline pool low aromatics blend-stocks (such as alkylates, isomerates, or oxygenates). Most Asian refineries have low reforming capacity. Therefore, the aromatics are relatively low and the reduction to the Euro 4 aromatics standards would require no significant capital investments. However, additional high octane blend-stocks or specialized additives that increase octane will be required were Asia to increase modest 90-93 RON specifications to the European octane requirements. The availability of these additives is limited; also, some have serious health and environmental concerns, as discussed in chapter 4. Overall, the reduction in aromatics, along with a concurrent increase in octane requirements, would create another challenge for the refining industry in Asia.

ii. Benzene

181. Benzene content could be slightly reduced by reducing reformer severity for aromatics. However, a reduction of benzene to the Euro 4 limit (1% by volume) would require either a benzene extraction unit or a reformate (or naphtha) fractionation unit combined with a benzene saturation unit. Most Asian refiners would require additional capital investments to reduce benzene.

iii. Olefins

182. Olefins content could be reduced to the Euro 4 levels (18% by volume) by hydrotreating the high olefins gasoline components (usually fuel catalytic cracking [FCC] gasoline) or by reducing FCC severity. Preliminary data indicate that in a number of Asian refineries the olefins are quite high, and reducing olefins would be an issue. However, olefins content could be significantly reduced by hydrotreating both the FCC gasoline and the FCC feed to reduce the sulfur content. The reductions in olefins content would also lower octane values and would further exacerbate the octane challenge discussed above.

iv. RVP

183. The majority of Asian refineries produce gasoline with RVP higher than the Euro 4 standard. The RVP is reduced to about 50-60 kPa by limiting the blending of light components such as butanes into the gasoline blending pool. This would not require significant capital investment, but it would downgrade the monetary value of butane. Additional reductions in RVP would require a fractionation unit to allow the removal of certain light hydrocarbons (C4 and C5 streams) from the gasoline pool. These compounds could be excluded from the gasoline pool and used for the production of oxygenates, alkylates, or petrochemicals. However, this would require additional capital investments, and some portion of the C4 and C5 might be reduced in value.

v. Distillation

184. Data for fuels produced in Asia are insufficient to evaluate the impact of such a requirement. The reductions in T90 (or E150 in EU standards) would require a fractionation unit to remove the heavier fuel components from the gasoline pool, isomerization, or the blending of oxygenates. Oxygenates in many cases would be sufficient to reduce T50 (or E100 in EU standards) to acceptable levels.

vi. Sulfur

185. Although a number of Asian countries have road maps to reduce the sulfur content of gasoline, in some, the gasoline produced still has a high sulfur content, and there are no plans to lower the sulfur content. The hydroskimming refineries in Asia are well-positioned to meet the Euro 4 sulfur content standards without significant capital investments. However, reductions in sulfur content would require additional capital investment in most of the complex refineries. In countries where the 500 ppm limit is in place for sulfur, there is hydrotreating capacity for either gasoline or gasoline blend-stocks. In this case, produced gasoline usually has average sulfur content below the 500 ppm. However, a reduction to Euro 4 levels (50 ppm or lower) would require the hydrotreating of most of the gasoline blending components such as the straight run, the FCC gasoline, and/or the feed into the FCC unit. New processes and more effective catalysts are sufficient to reduce sulfur content to the 10 ppm limit and require much smaller capital investments. An optimized strategy to meet the 50 ppm standard would involve the installation of process units, allowing future modifications to produce gasoline at the 10–20 ppm limit.

b. Diesel

i. Sulfur

186. Some Asian countries already produce diesel fuel with a sulfur content of 500 ppm. For these countries, the reduction to Euro 4 levels would require either a new high-pressure hydrotreating unit or the conversion of an existing one-stage hydrotreater to a two-stage hydrotreater. In the United States, refiners in the past have used higher-pressure hydrotreating units. Because of new developments in process technology, lower pressure units with high activity catalysts are capable in some cases of producing Euro 4 compliant diesel fuel. The high-pressure units are much more expensive. The ability to use a lower pressure unit is a function of the amount of light cycle oil in the diesel blend. The more light cycle oil in the blend, the more difficult it is to treat and the more likely it is to require the use of a high-pressure hydrotreating process. In most Asian countries, light cycle oil in diesel are in low amounts, making the use of lower pressure units feasible.

187. For refiners that are currently producing diesel with sulfur content much higher than 500 ppm, a high-pressure hydrotreater could reduce sulfur levels to 50 ppm. However, if they choose to first reduce the sulfur content to 500 ppm with the use of a medium severity hydrotreater, further reduction of sulfur content to 50 ppm would still require the installation of a high-pressure hydrotreater and possibly a two-stage hydrotreating process with the use of different catalysts. Larger process units may also be needed to lengthen catalyst cycle time. A critical decision for most refineries is whether to use an incremental or one-step approach. Fuel quality regulators must consider the potential cost savings for refiners of the one-step approach in setting their medium-term fuel quality road maps. Some studies show that further reducing sulfur content to 10 ppm may require the installation of new hydrocrackers. However, it is

expected that a high-pressure hydrotreating unit with advanced catalysts would be the norm in most cases. Sulfur reduction strategies require a careful optimization to implement an approach that would provide for long-term capability and reduce long-term costs. International experience has demonstrated that the one-step approach is preferred. However, if a phased-in introduction of the standards is desired, care should be taken to minimize the number of steps. In a two-step approach, a single large high-pressure unit could be installed and operated initially at lower severity to produce 350 ppm sulfur. The unit could be modified and operated later at higher severity to produce very low sulfur content diesel fuel.

ii. Distillation

188. Although data on the distillation properties of Asian fuels is insufficient to draw firm conclusions, the limited data available indicate that the Euro 4 standards distillation properties can be met in some countries without additional processing. In general, to reduce distillation, heavier components would need to be selectively separated and removed from the diesel blending pool. The capital costs of such an approach would be small. However, it would reduce the diesel volume and would have an economic penalty for the refiner, as it would downgrade the value of this component that would find its way into the fuel oil pool.

iii. Cetane Improvements

189. Most Asian refineries comply with the cetane standards and would not experience cetane shortages. If needed, cetane additives could increase cetane content without additional capital investment.

3. Costs of Process Options

190. All studies show that the production of cleaner fuels would involve significant capital investments to modify existing, and to install new, refinery processes. Table 3.5 shows a range of capital costs for the various refinery processes as it has been used in various studies of this subject. The data are adjusted by using the Nelson-Farrar inflation index, maintained by the *Oil and Gas Journal* to reflect changes in refinery costs since the base year 1946. It is apparent from this table that there is a range in reported capital investment costs, which reflects either the differences in technology used or the differences in cost estimates provided by different suppliers for the various processes.

Table 3.5: Capital Investments for Refinery Processes Used in the Production of Cleaner Fuels

Process Unit	Capacity (MBBLS/SD)	Onsite Investments (2005) Range of Costs (US$ million)
Heavy Naptha Splitter	15	9
Benzene Saturation	5	13 to 22
Isomerization	6	14 to 26
Naphtha Hydrotreater	20	27 to 33
FCC Gasoline Hydrotreater	20	29 to 32
Gasoil Desulfurization	20	31 to 56
Alkylation	7	40 to 118
HP Gasoil Desulfurization	20	55 to 77

FCC = fuel catalytic cracking, HP = hydroprocessing, MBBLS/SD = million barrels per stream day.
Source: J. Courtis, based on studies in footnote 19.

191. In estimating the total costs of production, other external factors need to be considered such as off-site costs and operating costs. Off-site costs include those for support equipment (such as pumps and piping), land, and other related costs. Operating costs represent the energy consumption, maintenance, personnel costs, and material (e.g., catalysts). Adjustments to the estimates are based on the assumption that off-site costs represent 20% of capital costs and that operating costs represent 10% of the annualized capital costs. The capital recovery is assumed to be at 7% interest for 10 years.

4. Costs of Production

192. Table 3.6 summarizes existing studies on the incremental cost of production of clean fuels in the EU, the United States, and Asia.[19] EU data may be useful for estimating potential Asian refinery costs because both groups of refineries are designed and operated to satisfy higher demand for distillates rather than for gasoline. However, EU refineries are more complex than Asian refineries, and the EU studies appear to assume higher costs for capital investments

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[19] Please see (i) footnote 6; (ii) CARB and California Energy Commission. 2003. *Reducing California's Petroleum Dependence*. Prepared by TIAX, LLC. Sacramento. Available: http://www.energy.ca.gov/reports/2003-08-14_600-03-005.PDF; (iii) National Energy Policy Office. 2002. *A Study on Changes in Specifications for Gasoline and Diesel Fuels in Thailand*. Prepared by Daedalus, LLC and ERM-Siam, Co., Ltd. Bangkok. Available: http://www.cleanairnet.org/caiasia/1412/article-58857.html; (iv)Trans-Energy Research Associates. 2002. *Improving Transport Fuel Quality in China: Implications for the Refining Sector*. Available: http://china.lbl.gov/node/85; (v) Environment Australia. 2000. *Setting National Fuel Quality Standards—Discussion Paper 1. Summary Report of the Review of Fuel Quality Requirements for Australian Transport*. Canberra. Available: http://www.environment.gov.au/atmosphere/fuelquality/publications/paper1.html; (vi) Arthur D. Little. 1993. *Modifying European Gasoline Composition to Meet Enhanced Environmental Standards and Its Impact on EC Refiners—Document C: Refinery Investment and Operations*. Berlin Arthur D. Little(vii) Japan Automobile Manufacturers Association (JAMA). 2004. *Fuel Quality in ASEAN Countries: JAMA Fuel Survey Results 2003/2004*; (viii) United States Environmental Protection Agency. 1999c. *Regulatory Impact Analysis - Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements*. Available: http://www.epa.gov/tier2/frm/ria/r99023.pdf; and (ix) United States Environmental Protection Agency. 2000. *Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*. Available: http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm

than those used in all of the other studies. The US refineries target production of gasoline, but the capital cost assumptions for process equipment used in the US studies are more current and reflect current process technologies. The Asian studies (e.g., Japan Automobile Manufacturers Association [JAMA], Australia, Thailand, PRC, and Asia) appear to more accurately represent the real costs to Asian refineries. In particular, JAMA produced a helpful study for estimating the costs of sulfur reductions at both a small refinery and a more complex one. Table 3.6 includes some adjustments to the costs estimated by JAMA and incorporates off-site costs and the costs of hydrogen production. The costs in the 2003 California study are actual costs that were determined when the cleaner fuels had been produced. It should be noted that all studies have used EU or US labor cost estimates, but construction costs in Asia are expected to be lower than in the United States or EU.[20]

193. In all of the studies, the methodologies tend to underestimate the costs for some refineries and to overestimate the cost for others because the composite refinery model used does not consider variability among refineries.

[20] In its comments, the oil industry indicated that construction costs in Asian countries can be 20% lower than those in either the US or the EU.

Table 3.6: Cost Estimates from Various Studies

Studies	Region	Fuels Studied	Study's Objectives	Incremental Cost Of Production (US cents/liter)
California[a] (2003)	California	Gasoline	S: 150 ppm → 30 ppm RVP: 62 kPa → 48 kPa Aro: 35% → 22% Ole.:15% → 10% Benz.: 2% → 1% Distillation ↓	2.64
		Diesel	S: 800 ppm → 370 ppm Aro.: 28% → 10%	1.6
			S: 370 ppm → 15 ppm	0.6-0.7
Arthur D. Little[b] (1993)	Europe	Gasoline	S: 800 ppm → 100 ppm Aro: 40% → 35% Benz.: 3.2% → 1%	2.8-3.0
Daedalus[c] (2002)	Thailand	Gasoline	S: 175 ppm → 50 ppm RVP: 59 kPa → 48 kPa Benz.: 2.4% → 1%	1.6
		Diesel	S: 500 ppm-50 ppm	0.6
Enstrat[d] (2003)	All Asia	Diesel	S: 2,200 ppm → 50 ppm	2.1-3.3
Australia Government[e] (2000)	Australia	Gasoline	S: 193 ppm → 50 ppm Benz: 2.9% → 1.0%	0.7
		Diesel	S: 1,500 ppm → 50 ppm	1.1
Trans-Energy[f] (2002)	PRC	Gasoline	S: 500 ppm → 50 ppm Ole.: 35% → 14% Aro.: 40% → 35% Benz.: 5% → 1%	0.5
		Diesel	S: 500 ppm → 50 ppm T95: 370 → 340	0.8
JAMA[g] (2004)	Asia	Diesel	S: 500 ppm → 50 ppm	Small: 1-1.4 Large: 0.7-0.8
		Gasoline	S: 500 ppm → 50 ppm	Small: 0.3-0.4 Large: 0.2
US[h] (1999)	US	Gasoline	S: 270 ppm → 30 ppm	0.4-0.6
US[i] (2000)	US	Diesel	S: 500 ppm → 15 ppm	1.2

Aro = aromatic, Benz. = benzene, JAMA = Japan Automobile Manufacturers Association, kPa = kilopascal, Ole. = olefin, ppm = parts per million, RVP = Reid vapor pressure, S = sulfur, US = United States.

[a] California Air Resources Board and California Energy Commission. 2003. *Reducing California's Petroleum Dependence*. Prepared by TIAX, LLC., Sacramento. Available: http://www.energy.ca.gov/reports/2003-08-14_600-03-005.PDF

[b] Arthur D. Little. 1993. *Modifying European Gasoline Composition to Meet Enhanced Environmental Standards and its Impact on EC Refiners – Document C: Refinery Investment and Operations*. Berlin: Arthur D. Little

[c] National Energy Policy Office. 2002. *A Study on Changes in specifications for Gasoline and Diesel Fuels in Thailand*. Prepared by Daedalus LLC and ERM-Siam, Co Ltd. Bangkok. Available: http://www.cleanairnet.org/caiasia/ 1412/article-58857.html

[d] Asian Development Bank (ADB). 2003a. *Cost of Diesel Fuel Desulphurisation for Different Refinery Structures Typical of the Asian Refining Industry*. Prepared by Enstrat International, Ltd. Manila: ADB. Available: http://www.cleanairnet.org/ caiasia/1412/articles-40677_EnstratSulphurReport.pdf
[e] Environment Australia. 2000. *Setting National Fuel Quality Standards – Discussion Paper 1. Summary Report of the Review of Fuel Quality Requirements for Australian Transport*. Canberra: Environment Australia. Available: http://www.environment. gov.au/atmosphere/fuelquality/publications/ paper1.html
[f] Trans-Energy Research Associates. 2002. *Improving Transport Fuel Quality in China: Implications for the Refining Sector*. Available: http://china.lbl.gov/node/85.
[g] Japan Automobile Manufacturers Association. 2004. *Fuel Quality in ASEAN Countries: JAMA Fuel Survey Results 2003/2004*.
[h] United States Environmental Protection Agency. 1999c. *Regulatory Impact Analysis - Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements*. Available: http://www.epa.gov/tier2/frm/ria/r99023.pdf
[i] United States Environmental Protection Agency. 2000. *Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*. Available: http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm

Source: J. Courtis, from studies referenced in above notes.

194. A careful review of the study results summarized in Table 3.6 shows some internal consistency. The studies show that a reduction in sulfur content of gasoline from 500 ppm to 50 ppm ranges in cost from 0.18–0.80 US cents per liter. When additional properties such as benzene, aromatics, and RVP (Thailand case) are controlled, the costs increase to about 1.6 US cents per liter, or to 2.6 US cents per liter if the distillation, olefins, RVP, aromatics, and benzene are decreased to very low levels (California case). The only cost outside this range is the cost estimated in a 1993 study by Arthur D. Little (footnote 19[vi]) for the implementation of the Euro 3 standards. This study assumed high costs for the necessary capital investments, sometimes two to three times the costs assumed by other studies. As an older study, these estimates do not reflect current understanding of capital process costs.

195. With regard to diesel, these studies indicate that the reductions in diesel sulfur content from 500 ppm to 50 ppm would cost about 0.53–0.80 US cents per liter. The US EPA costs are slightly higher at 1.16 US cents per liter, given the reduction in sulfur content to 15 ppm. The Australian costs are also higher at 1.11 US cents per liter but require the reduction in sulfur from 1,500 ppm to 50 ppm. The JAMA study[21] indicates that the costs for small refineries would be in the range of 0.98–1.37 US cents per liter versus lower costs for the large refineries. The California costs derived from actual data after implementation are higher, about 1.59 US cents per liter, because they include the cost of hydrodearomatization that would not be required for compliance with Euro 4 standards. The cost estimates by Arthur D. Little (footnote 19[vi]) and Enstrat (footnote 6) are also at the high end of the spectrum. Both of these analyses include significantly higher capital costs for high-pressure hydrotreating units.

196. Some studies have separately evaluated the cost of reductions in sulfur content from 50 ppm (Euro 4) to 10 ppm (Euro 5). The Purvin & Gertz study[22] estimated this cost to be in the range of 0.11–0.29 US cents per liter for gasoline. The same study estimates the cost for diesel to be 0.29–0.61 US cents per liter, while the Enstrat (footnote 6) study for Asia estimates it to be about 0.03 US cents per liter. Assuming that refiners design the Euro 4 compliance so as to comply with the Euro 5 at a future date, costs are likely to be at the lower end of the cost spectrum discussed above.

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[21] Japan Automobile Manufacturers Association (JAMA). 2004. *Fuel Quality in ASEAN Countries: JAMA Fuel Survey Results 2003/2004*. Japan. 2004.
[22] European Commission (EC) Directorate-General Env.3. 2000. *ULS Gasoline and Diesel Refining Study*. Brussels: European Commission

197. All of the studies highlighted in Table 3.6 used generally similar technology for the refinery retrofits to improve the RVP, aromatics, olefins, and benzene content. The differences are in the type of technologies used for the sulfur reductions, with some studies assuming that high-pressure units or multistage processes, rather than lower pressure processes, would be required. This assumption changes the capital and operating costs significantly. Another major difference in the costs results from the capital costs assumed for some of the processes, which in some cases are excessively high.

198. Although the average estimated costs appear consistent, clean fuel implementation costs would likely vary significantly among refineries. Such costs would reflect differences in local starting fuel specifications, refinery configurations, crudes available in the marketplace, and the relative balance between the motor gasoline and diesel markets. In addition, the opportunity to dispose of low-value by-products depends on the existence of neighboring industries that would require such by-products.

E. Benefits of Producing Cleaner Fuels

199. Cost-benefit studies on adopting low sulfur fuel and cleaner vehicles have been conducted in the United States, PRC, Mexico, and elsewhere. These studies show that adopting low sulfur fuels in combination with more stringent vehicle emission standards leads to benefits that far outweigh the costs of adopting those programs. For the PRC, a 2006 International Council on Clean Transportation study[23] looked at the costs and benefits of reducing the sulfur content of fuels to 10 ppm in combination with adopting ever more stringent vehicle emission standards. Lowering the sulfur content of gasoline and diesel produces important benefits. Air quality should improve immediately because the low sulfur fuel is used by both new and older vehicles. The largest benefits are realized when low sulfur fuels are combined with stricter vehicle emission standards. Health benefits, for example, increase by a factor of three to four when the vehicle emission standards are combined with the low sulfur fuel. Overall, the combination of low sulfur fuels and new vehicle standards showed a benefit to cost ratio of about 20:1, demonstrating that this approach is a very cost-effective tool for reducing the negative impact of vehicle emissions on public health. The health benefits included decreased premature mortality, chronic and acute bronchitis, asthma, and restricted activity days.

200. Over the past several years, the United States has issued various regulations reducing the sulfur content of gasoline and diesel fuels and has set new emission standards for cars, trucks, buses, and construction equipment. The benefits of these programs have been shown consistently to far outweigh the costs. Under the low sulfur diesel fuel portion of US EPA's heavy-duty highway diesel rule, which took effect in June 2006, refiners are producing cleaner-burning ULSD fuel for use in highway vehicles. This new diesel fuel costs from 1.1 to 1.3 US cents more per liter to produce and distribute. ULSD enables advanced pollution control technology for heavy-duty trucks and buses so that engine and vehicle manufacturers can meet new 2007 emission standards. As a result, each new truck and bus is more than 90% cleaner than past models. The introduction of ULSD also enables light-duty passenger vehicle manufacturers to make use of similar technologies on diesel-powered cars, sport utility vehicles, and light-trucks.

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[23] International Council on Clean Transportation (ICCT). 2006. *Costs and Benefits of Reduced Sulfur Fuels in China*. Washington, DC Available: http://www.theicct.org/documents/Reduced_Sulfur_China_ES_ICCT_2006.pdf

201. US EPA's Clean Air Highway Diesel final rule required a 97% reduction in the sulfur content of highway diesel fuel, from 500 ppm to 15 ppm. ULSD became available at retail stations beginning in the summer of 2006. As of 15 October 2006, refiners were required to produce 80% of their diesel fuel at the 15 ppm standard. Model 2007 cars, trucks, and buses with advanced pollution control became available in the autumn of 2006. By addressing diesel fuel and engines together as a single system, this regulation will provide annual emission reductions equivalent to removing the pollution from more than 90% of today's trucks and buses, or about 13 million trucks and buses, by 2030 when the current heavy-duty vehicle fleet will have been completely replaced. This is the greatest reduction ever achieved in harmful emissions by cars and trucks of soot, or PM.

202. Once this regulation is fully implemented, environmental benefits will include annual emission reductions of 2.6 million tons of smog-causing NO_X and 110,000 tons of PM. In the long term, more than US$70 billion in environmental benefits and approximately US$15 billion in public health benefits will be realized annually. Health benefits will include the annual prevention of 8,300 premature deaths; 5,500 cases of chronic bronchitis; 17,600 cases of acute bronchitis in children; 360,000 cases of respiratory symptoms in asthmatic children; and 1.5 million lost work days.[24]

203. A 2006 study by Mexico's environmental agency [25] looked at the costs and benefits of an integrated clean fuels and vehicles program, concluding that the benefits outweighed the costs by a ratio of 2.4:1. Among the estimated health benefits for 2006–2030 are avoidances of approximately 56,000 premature deaths; 166,000 cases of chronic bronchitis; 5.6 million lost work days; and 78 million restricted activity days due to respiratory illnesses.

204. Although these studies involve different countries, they demonstrate in all three cases that the benefits of clean fuel and vehicle programs outweigh the costs, and thus represent sound public policy choices.

F. Introducing Cleaner Fuels in Phases

205. Regulatory agencies in Europe, the United States, and Asia have taken different approaches to introducing both fuels and motor vehicle standards. The approaches reflect (i) the magnitude of the air quality problem in each particular region and the contribution of fuels and motor vehicles to that problem, (ii) the technical understanding of the fuel emissions and the impacts of fuel properties on motor vehicle emissions, (iii) advances in vehicle emission control technology, (iv) the political will in each region to implement fuel standards that would have a significant economic impact on the regulated industry, and (v) the economic impacts on consumers and each region's economy. The approaches fall into three general categories:

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[24] United States Environmental Protection Agency (US EPA). 2000. *Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*. Available: http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm

[25] Secretaria de Medio Ambiente y Recurso Naturales (SEMARNAT), Instituto Nacional de Ecologia, and Pemex Refinacion. 2006. *Estudio de Evaluacion Socioeconomica del Proyecto Integral de Calidad de Combustibles: Reduccion de Azufre en Gasolin y Diesel*. Mexico City

1. Implement a Gradual Approach

206. A gradual strategy would allow the phased and concurrent introduction of fuels and motor vehicle standards with a defined and clear road map for implementation. The United States and the EU took this approach for three main reasons:

(i) gradual advances in vehicle technology required improved fuel quality,
(ii) implementation of small initial improvements in fuel quality were not sufficient to reduce emissions to satisfactory levels, and
(iii) detailed impacts of fuels and motor vehicles on ambient air quality and on public health were initially not well understood.

207. In both the EU and the United States, the fuel standards became progressively stricter, and road maps were implemented over a number of years. Other countries have followed this approach and have established different road maps and implementation timeframes. Thailand, for example, has established a road map for lead phase out and a road map for progressively tighter Euro 2, 3, and 4 standards for both fuels and motor vehicles. A similar approach has been taken by PRC, India, Taipei,China, and other Asian countries. Gradual product quality phasing is especially being considered by developing countries with a regulated fuels market when there are constraints such as the difficulty of raising capital and of passing on the cost of refinery modification to consumers.

208. Both the refining technology to produce Euro 2, 3, and 4 fuels and the technology to produce Euro 4 vehicles are well understood. The technology to produce Euro 5 fuels and vehicles is also now well understood. In most Asian metropolitan areas, the severity of the air quality problem, combined with the expected growth in both fuel consumption and vehicle use, requires a reduction in motor vehicle emissions to the lowest possible level as soon as possible. This will require the cleanest fuels possible. The gradual approach in all cases would delay achievement of air quality improvements.

209. The gradual approach will increase the cost of compliance. For example, reductions in sulfur content to 50 ppm can be achieved gradually by the use of a medium-pressure hydrotreater to first reduce sulfur to 500 ppm, and then by later adding a high-pressure hydrotreater to further reduce sulfur to 50 ppm. The combination of medium- and high-pressure hydrotreating is more expensive than the initial construction of a high-pressure unit to produce 50 ppm sulfur content fuel. An analysis by Enstrat (footnote 6) for Indonesia, Malaysia, and Singapore found an increase in cost of about 10%–20% when the gradual approach rather than the one-step approach is taken.

2. Implement Initial Fuel Quality Standards and More Comprehensive Standards Later

210. In most Asian countries, the emphasis on cleaner fuels has been to improve specific fuel properties to enable the efficient operation of motor vehicle emission control technologies such as catalytic converters.

211. An example of this approach is the removal of lead from gasoline, and most recently the emphasis on the reductions of sulfur content for both gasoline and diesel fuels. These strategies will no doubt reduce emissions. The lead reductions allow reductions in ambient lead concentration and the introduction of catalytic systems. The implementation of sulfur content standards produce immediate benefits from the entire fleet, and these benefits multiply dramatically when combined with the use of advanced emission control devices. However, an

important disadvantage of concentrating on the sulfur content only is that some fuel properties such as olefins and aromatics content reduce the performance of engine components. Although there is a belief that the use of deposit control additives would minimize the adverse impacts of aromatics and olefins on engine components, no effective program at present could ensure the use of effective and appropriate deposit control additives in Asia. The reductions in benzene and aromatics also have an impact on ambient toxic levels. The reductions in RVP have a significant effect on ozone formation that is very important in hot ambient environments experienced in Asia.

212. Regulatory agencies in the EU and the United States have recognized the shortcomings of concentrating on just one property, and thus have required implementation of multiple fuel property standards. A systemic approach of looking at all fuel properties together requires a balanced set of specifications but also offers long-term cost benefits to refiners. It would be much more costly and problematic for refiners to implement additional improvements in fuel quality in the future. Although the advantage of concentrating on one or two priority properties is that it reduces the short-term cost of compliance and delays the capital investments needed to improve the other properties until a later date, the obvious disadvantage is that implementation of improvements in other properties would be delayed and overall air quality improvements might also be delayed.

3. Implement Higher Fuel Quality Standards in Cities and Regions where Air Quality Is an Issue and Lower Standards Elsewhere

213. Another option that has been discussed is the limited introduction of clean gasoline and diesel fuel standards only in control areas or cities where the air quality problem is a major issue. Different fuels may be marketed throughout the remainder of the country.

214. This approach was implemented in the United States, where California was allowed to implement stricter fuel and motor vehicle standards than the rest of the country because of the severity of its air quality problem. The same approach was also implemented in other areas of the United States. Fuel standards are strict for so-called non-attainment areas (areas where air quality problems are severe) and less restrictive in areas where the air quality is acceptable. For areas where CO is an air quality problem, the use of oxygenates in fuel is required. The same approach was followed in Sweden where very strict standards were implemented for diesel fuel used for certain classes of vehicles, and different standards apply to the rest of the country. In the PRC and India, stricter emission and fuel standards are in force for selected cities.

215. In all cases, when less restrictive standards outside of a control area were allowed, restrictive market and enforcement mechanisms were employed to minimize the use of out-of-compliance fuels in the control areas. In addition, officials determined that the fuel production, marketing, and distribution systems were capable of handling the marketing and distribution of multiple products. Different storage tanks for storing and distributing different products were used at refineries and at terminal facilities. Governmental fuel quality monitoring was extensive, and heavy monetary penalties were assessed for violations of standards. It should be noted that limited introduction has significant environmental implications when it is used for properties such as lead or sulfur content. Contamination of fuels in the control areas could result either in damage of emission control systems or in permanent reductions in their emission control efficiency.

216. To be effective, this approach must be carefully designed, and a number of factors must be considered:

(i) The fuel production, marketing, and distribution system must be able to produce, segregate, and market two different grades of fuel.
(ii) The quality of fuels in the uncontrolled areas should be carefully monitored to avoid backsliding. Once clean fuels are introduced, it is possible that refiners will reject from the fuel pool used in the controlled area blend-stocks that have undesirable properties. Some of these unwanted blend-stocks might be marketed or used as blend-stocks for fuels sold in uncontrolled areas, resulting in the deterioration of fuel quality in those areas.
(iii) Additional resources are required to avoid the penetration of lower quality fuels from the uncontrolled to the controlled areas, and to avoid fuel adulteration in areas under control.

G. Demand and Supply Development

217. The supply of and demand for cleaner fuels have to be considered within the broader context of supply and demand for fuels. Although the bulk of the gasoline produced finds its way into the motor vehicle market, a significant portion of the distillate pool is used for the unregulated markets (e.g., kerosene and fuel for power generation).

218. Available data indicate that in a number of countries there is an excess capacity or a potential for capacity expansion. The refineries in Indonesia, Republic of Korea, Malaysia, Pakistan, Singapore, Taipei,China, and Thailand have already made limited modifications, appear to have the capacity to meet current demand for fuels, and have established some capacity to satisfy the short-term demand for Euro 3 and 4 type fuels. For India, the existing refining system appears to be capable of satisfying the current demand, with some capacity for exports. In addition, India has announced plans for refinery expansions and for building another major refinery that would provide additional exporting capacity. In the PRC, demand is currently satisfied, although there are some imports from the Republic of Korea and Japan, and a small amount of exports.

219. Three factors could limit potential increases in the supply of cleaner fuels:
(i) Some refineries, most likely in the case of smaller refiners (including some hydroskimming facilities), might choose not to invest in the capital expenditures necessary to produce cleaner fuels.
(ii) Some refineries might choose to reduce capital investments and reduce fuels production capacity.
(iii) Implementing operational changes could lead to yield losses.

220. However, a number of factors may increase supply:
(i) Healthy refinery margins during the last few years and the ability to adjust prices to recover capital investments will support additional capital investments for refinery expansions and process modifications.
(ii) The production of biofuels (ethanol and biodiesel) is increasing throughout the region. A number of countries in Asia are actively pursuing the production of biofuels to support the agricultural sector and to meet greenhouse gas reduction needs.
(iii) Refinery expansions are in the planning stages for a number of countries. The building of new refineries is ongoing or planned for the PRC and India.
(iv) Activities at the major merchant oil processing centers may help increase the supply of cleaner fuels or the supply of better quality blend-stocks. Refiners in Singapore and in the Middle East are in the process of building additional

process units to increase their capacity to produce cleaner fuels or cleaner blend-stocks. However, these better quality products would only find their way to Asian markets if prices were adequate because demand for cleaner fuels and blend-stocks is increasing in many developing countries, and prices in the EU and the United States are increasing.

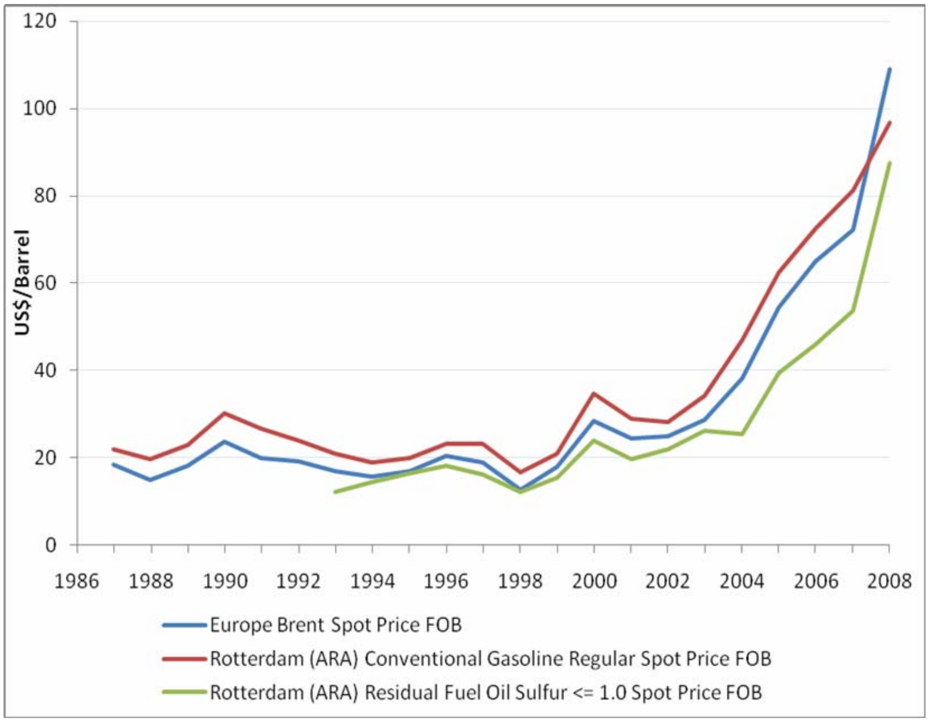
H. Availability of Capital and Trained Labor

221. The availability and cost of capital are important considerations that would significantly impact both the costs of production of cleaner fuels and the ability of refiners to modify their refineries. The availability and the cost of capital would be different among refiners, reflecting the financial strength of the refiner, the refiner's ability to recover capital and operating expenditures, and the industry overall. A market system enhances the ability to recover expenditures, assuming that all producers experience similar expenditures. In markets where the prices are controlled, the potential difficulty to recover the costs through a price adjustment mechanism makes the refiners' ability to raise capital an issue. Unless a price adjustment is implemented, the ability to raise the capital is reduced.

222. Given current fuel and product prices, raising capital may not be a major problem.[26] Figure 3.7 shows the historical evolution of fuel prices from 1987 to 2008. Nevertheless, the availability of capital may be a factor in countries with refineries but no income from oil exploration, and those with a regulated fuel market unable to pass on costs for refinery upgrades to consumers.

[26] A Rand Corporation survey of US refining executives found that many discussants did not consider capital availability a critical issue.

Figure 3.7: Rotterdam Oil Product Spot Prices, 1987–June 2008
(US$/bbl)



ARA = Amsterdam-Rotterdam-Antwerp, FOB = free on board, US$/bbl = US dollars per barrel.
Source: United States Department of Energy, Energy Information Administration. 2008. Available: http://tonto.eia.doe.gov/dnav/pet/ pet_pri_spt_s1_d.htm

223. In addition, small, privately owned refineries may still face difficulties, or the cost of capital for them may be higher. For small refineries owned by governmental entities, the decision may be one of governmental policy and security of the fuel supply.

224. The availability and costs of trained personnel are very likely to differ from refinery to refinery, and from country to country, and may be a major issue in a number of Asian countries. Experienced engineering and construction services, along with well-trained labor, would be required for revamping refineries. In some Asian countries, these services were limited and had to be imported. However, since the late 1990s, the continuous upgrades and modifications of refineries in Asia have created an experienced labor force that would be helpful with future modification and construction. It should be noted that the costs of labor are much lower in Asia than in the United States and the EU. If all refinery modifications are done at the same time across Asia, the availability of sufficient trained labor, as well as of engineering and construction services, may prove to be a problem.

I. Conclusion

225. The current ability of Asian refineries to produce cleaner fuels that would comply with the Euro 4 standards is limited. A small number of refineries have the capacity to produce limited amounts of Euro 4 equivalent fuels in PRC, India, Singapore, Taipei,China, and Thailand, as well as in a number of countries where marketed fuels have properties similar to Euro 3 or Euro

4. For countries with a road map for implementing Euro 3 or Euro 4 standards, some refiners have announced investments for the production of cleaner fuels. An expansion of refining capacity, which is now becoming more likely after a long period of stable refining capacity in Asia, will most likely increase the volume of cleaner fuels. Decision makers can set cleaner fuel production targets by evaluating the impact on regional fuel supply; evaluating special characteristics of the refining industry in each country; and considering compliance flexibility options, weighed against impacts or benefits.

226. Refiners will need to install new process units as part of a retrofit for producing Euro 4 fuels. The ability to finance the large capital investments required may be a critical obstacle. Generally, the willingness of refiners to invest in the production of cleaner fuels is a function of their ability to recover expenditures through price adjustments. However, the current high fuel price environment, with high refinery profits, likely enhances their ability to raise the necessary capital.

227. Various studies indicate that the incremental costs of compliance with the sulfur content limits are on average about 0.2–0.8 US cents per liter for gasoline and 0.5-0.8 US cents per liter for diesel. Further reductions to the Euro 5 level would add about 0.6 US cents per liter to the cost of compliance. The improvements in other Euro 4 properties for gasoline such as olefins, RVP, benzene, and aromatics could increase the cost to about to 1.6 US cents per liter. The cost associated with producing low sulfur fuels is relatively small compared to changes in the global price of oil, and the public health benefits are certainly worth the investment.

228. For the large Asian refineries that produce the bulk of transport fuels for Asia, the implementation of cleaner fuel standards is not expected to significantly affect fuel production given sufficient time. Short-term regional demand is likely to be met through planned increases in supply resulting from the new refineries that are scheduled to come on line through planned expansions, or through increases in utilization rates.

229. Small refineries in Asia, which are still relatively large in number but small in production capacity, would experience higher costs of compliance. Capital investments required to produce Euro 4 fuels may be uneconomical for these refineries. However, protective mechanisms at the country level could allow some to continue contributing to the motor vehicle fuels market. Such an approach may not be sustainable in the long term and under a free market environment. Temporarily less restrictive standards, or a different compliance schedule as the need arises, might be ways to address the issue of small refineries. However, care should be taken so that the benefits of the standards would not be affected.

230. The full implementation of local programs targeting the increased production of biofuels, as well as the implementation of fuel economy standards, would have a significant impact on supply and demand for motor vehicle fuels in the region.

231. Compliance flexibility or flexibility in standards may provide significant reductions in operating costs and reduce market volatility. Any number of flexibility mechanisms might be employed; care should be taken to avoid significant reductions in benefits.

IV. ENHANCING OCTANE IN GASOLINE

A. Introduction

232. This chapter reviews relevant public-domain information sources documenting the direct and indirect impacts of the use of octane-enhancing metallic additives and oxygenates on health, vehicle emissions and performance, and the refining process.

233. Octane is a measure of a fuel's ability in an internal combustion engine to resist premature detonation, known variously as "auto ignition," "pinging," or "knock." If allowed to happen, premature detonation wastes energy in the fuel and can potentially permanently damage the engine. In older engines, it is eliminated by using a gasoline with an adequate octane number.

234. Vehicles are designed and calibrated by their manufacturers to operate with gasoline of a certain minimum octane rating. Many modern engines are equipped with knock sensors and can handle lower octane levels by automatically retarding the spark timing. However, fuel consumption, driveability, and power will suffer, and at very low octane levels knock may still occur.

235. Using gasoline with a higher octane rating than the manufacturer recommends usually does not improve the vehicle's performance.[27] It does not make the vehicle operate better, go faster, get better mileage, or run cleaner. Many vehicle owners erroneously believe that it is beneficial to use higher octane levels than are really necessary. Thus, motorists should be discouraged from using octane higher than that required by the vehicle manufacturer.[28]

236. A refinery's ability to produce gasoline at the specified octane value for each grade varies and is a function of the refinery's complexity and configuration. As the demand for different fuels shifts, refineries in Asia may not always continue to have the processing capability in place to meet the volume of fuel demanded by consumers at the required (minimum) octane rating. As the previous chapter indicates, the bulk of transportation fuels in Asia already come from large complex refineries, while a relatively small amount comes from small, mostly topping, or hydroskimming refineries.

237. To enhance octane, refiners can[29] (i) modify or redesign refineries and import selected crude oils or high octane blend-stocks (as described in detail in chapter 3), and (ii) use metallic additives or oxygenates.

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[27] European Automotive Manufacturers Association (ACEA), Alliance of Automobile Manufacturers (Alliance), Engine Manufacturers Association (EMA), and JAMA. 2006. *Worldwide Fuel Charter, Fourth Edition*. Available: http://oica.net/wp-content/uploads/2007/06/wwfc-fourth-edition-sep-2006.pdf

[28] For a further discussion on octane, see also the *Worldwide Fuel Charter*, a document developed by the world's automobile manufacturers, and cited in the previous footnote.

[29] Australian Institute of Petroleum. 2005. Submission to the Australian Government Biofuels Taskforce.

B. Octane Enhancers

1. Metallic Additives

238. The principal compounds used as metallic additives are many.

a. Lead Alkyls—TEL and TML

239. Lead alkyl additives were first used as inexpensive octane enhancers for gasoline in 1923. Most countries have since moved to ban lead in gasoline, due principally to an increased public awareness of the negative health effects associated with its use and a steady growth in the worldwide population of vehicles requiring unleaded gasoline to permit the use of vehicle emission control technologies such as catalytic converters and oxygen sensors.

240. The United States completely banned the use of lead as a motor vehicle fuel additive in 1995. Almost all Asian countries have since moved to do likewise. In the near future, transport will no longer be a source of lead emissions worldwide. According to the Partnership for Clean Fuels and Vehicles, leaded gasoline is now found in only 20 countries worldwide (Afghanistan, Algeria, Bosnia-Herzegovina, Former Yugoslav Republic of Macedonia, Fiji, Georgia, Iraq, Jordan, Democratic People's Republic of Korea, Laos, Mongolia, Montenegro, Morocco, Myanmar, Palestine, Serbia, Tajikistan, Tunisia, Turkmenistan, and Yemen).[30]

b. Iron Compounds—Ferrocene

241. Ferrocene (dicyclopentadienyl iron) is a coordination compound of iron and two molecules of cyclopentadiene. It is a metal-organic complex orange crystal with the smell of camphor which has a potential use as an additive to gasoline to prevent engine knock and as an additive to diesel fuel to facilitate trap regeneration.

c. Methylcyclopentadienyl Manganese Tricarbonyl (MMT)

242. MMT is a manganese-based compound marketed as an octane-enhancing fuel additive for gasoline, and has also been suggested for use in diesel fuel as a smoke-reducing additive (footnote 27).

2. Oxygenates

243. Oxygenated compounds are often added to gasoline to increase octane or extend gasoline supplies and to reduce the emission of such air pollutants as CO. Oxygenating the fuel also may modify vehicle performance or durability. The most widely used oxygenates are all organic based.

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[30] Please see (i) Partnership for Clean Fuels and Vehicles (PCFV) and United Nations Environment Programme (UNEP). 2007a. *West Asia, Middle East and North Africa Lead Matrix*. Last updated 22 January. Available: http://www.unep.org/pcfv/PDF/MatrixMENAWAJan07.pdf, (ii) PCFV and UNEP. 2007b. *Central and Eastern Europe + EECCA Leaded Gasoline Use*. Last updated March. Available: http://www.unep.org/pcfv/PDF/MatrixCEELeadMarch07.pdf, and (iii) PCFV and UNEP. 2007c. *Asia–Pacific Lead Matrix*. Last updated 14 August. Available: http://www.unep.org/pcfv/PDF/LeadMatrix-Asia-PacificAug07.pdf

a. Ethanol

244. Ethanol is a high-octane oxygenate that is currently produced principally in the United States and Brazil from renewable sources such as corn or sugar crops. Ethanol is completely soluble in gasoline and will be readily absorbed by any water present. A solvent, it is not easily transported by pipeline as it collects all the water and contaminants in the system; thus it must be transported separately from gasoline and mixed at the tanker prior to dispatch.

b. Methanol

245. Methanol is produced mainly from natural gas and is a traded chemical in the fuels market. It is used for producing MTBE and formaldehyde, has a very high octane value, high affinity to water, and is very corrosive. Engine manufacturers do not recommend its use in gasoline fuels.

c. Methyl Tertiary-butyl Ether (MTBE)

246. MTBE was once the most widely used fuel oxygenate because of its combination of high octane value, compatibility with gasoline and fuel system components, favorable effects on fuel properties (i.e., effects on distillation and dilution), and availability. It can be mixed with the fuel at the refinery and transported through pipelines. However, MTBE travels well in ground water and thus presents a major risk of contamination of ground water supplies from leaking fuel tanks as tiny amounts of MTBE affect the taste and odor of drinking water.

d. Ethyl Tertiary-butyl Ether (ETBE)

247. Ethanol can also be used to produce ETBE, which is about 42% ethanol and is produced by processing ethanol with isobutylene, usually made from natural gas. Auto manufacturers and refiners prefer to use ETBE in case they are required to use renewable fuels (footnote 27).

e. Tertiary-amyl Methyl Ether (TAME)

248. TAME is produced by a process similar to that for ETBE, although from methanol and isoamylenes. It shares MTBE’s excellent tolerance to water, and requires no changes to the refining, pipeline and distribution operation, or automotive technology.

C. Regulation and Use of Octane-enhancing Additives in Asia

249. Table 4.1 contains the current status of standards in Asia for octane-enhancing additives. The only country in Asia that permits the use of ferrocene is Viet Nam. India and Indonesia have banned the addition of manganese to gasoline. Although the use of MMT is permitted in some countries such as the PRC and Viet Nam, it currently is used only sparsely in the developed world. According to the manufacturer, it was being sold in about 30 countries in 2003.[31] MMT had been most widely used in Canada, where it was found in approximately 90% of gasoline after the phase-out of lead was completed. Currently, about 95% of Canadian gasoline is MMT-free. MMT is not allowed in California or in RFG in the United States, and it is used in less than 1% of all gasoline in the United States. It is not used in Japan or Germany. Since 2002, New Zealand has restricted manganese levels in gasoline to a maximum of 2.0

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[31] Afton Chemical Corporation. 2003. *2003 Annual Report*. Richmond, Virginia, U.S. 2003

milligrams of manganese per liter.[32] MMT is used in a few Eastern European countries. It was also used in Australia from 2001 to 2004 in a selectively marketed lead replacement gasoline, the marketing of which was discontinued due to poor demand. MMT was not used in unleaded gasoline, the most widely used product, or in other brands of lead replacement gasoline.[33] It is not allowed in India and restricted to 6 milligrams per liter in Beijing.

250. Compared with other fuel parameters, the use of additives is generally not well-regulated in many Asian countries.

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[32] Blumberg, Katherine, and Michael P. Walsh. 2004. *Status Report Concerning the Use of MMT in Gasoline*. Washington, DC ICCT. Available: http://www.theicct.org/documents/MMT_ICCT_2004.pdf

[33] Cohen, D. D., B. L. Gulson, J. M. Davis, E. Stelcer, D. Garton, O. Hawas, and A. Taylor. 2005. Fine-particle Mn and Other Metals Linked to the Introduction of MMT into Gasoline in Sydney, Australia: Results of a "Natural Experiment”. *Atmospheric Environment* 39: 6885-96.

Table 4.1: Overview of Regulation of Octane-enhancing Additives in Asia

Country	Government Regulation				Remarks
	Ferrocene	MMT	MTBE	ETBE	
Afghanistan	No specific regulations				
Bangladesh	No specific regulations				Importer is allowed to use octane-enhancing additives
Cambodia	No specific regulations				
PRC	Banned (GB17930-1999)	max 16 mg/l	Max 15% vol		Beijing has limited MMT to 6 mg/l since December 2007; PRC has limited to 16 mg/l
Hong Kong, China	No specific regulations		Max 15% vol for MTBE and ETBE		Gasoline specifications at EU 4 level. No additives are being used
India	Not used	Not allowed	Max 15% vol	Max 15% vol	Only the Numaligarh Refinery was found to have been using MMT, but its use has been discontinued since Mar 2006 following a ministerial decision
Indonesia	Not allowed as per Ministry of the Environment Decree No 141/2003		15% vol max for MTBE and ETBE		MTBE used from 1995 but discontinued in 1997. PERTAMINA has requested the Ministry of the Environment to allow the use of MMT and ferrocene following the complete phase out of leaded gasoline in 2006. The Ministry turned down the request of PERTAMINA to use MMT but allowed the use of ferrocene in the case of supply problems for high octane blend-stock with a provision that a permit is issued which will have a maximum validity of 6 months and which will be monitored by the ministry
Republic of Korea	Not used		2.8 mg/l to 2.8% vol (summer); 5.6 mg/l to 2.5% vol (winter)		
Lao PDR	No specific regulations				
Malaysia	No specific regulations				
Mongolia	No specific regulations				
Nepal	No specific regulations				
Pakistan	No specific regulations				No additives being used
Philippines	No specific regulations		Max 2% vol	Max 2% vol	A number of the smaller fuel importers use MMT while ferrocene is reportedly used by one of the major refiners in the country
Singapore	No specific regulations				
Sri Lanka	No specific regulations				No additives being used

Table 4.1: Overview of Regulation of Octane-enhancing Additives in Asia–*Continued*

Country	Government Regulation				Remarks
	Ferrocene	MMT	MTBE	ETBE	
Thailand	Not allowed		5.5 to 11% vol for MTBE and ETBE		MTBE is still being used but its use is expected to be reduced considerably once Thailand introduces gasohol on a large scale
Viet Nam	Max 5 mg/l (TCVN 6776–2005)		15% vol max for MTBE and ETBE		Actual use of MMT is limited

% vol max = percent by volume maximum, ETBE = ethyl tertiary-butyl ether, mg/l = milligram per liter, MMT = methylcyclopentadienyl manganese tricarbonyl, MTBE = methyl tertiary-butyl ether, PDR = People's Democratic Republic, PRC = People's Republic of China, PERTAMINA = Perusahaan Tambang Minyak Nasional (National Oil Mining Company).
Source: Data obtained by Clean Air Initiative for Asian Cities from among its members and *Worldwide Automotive Fuel Specifications*, January 2007 edition, International Fuel Quality Center.

D. Effects of Octane-enhancing Additives for Gasoline on Health

251. The health effects of different fuel additives may be evaluated based on several factors, including the degree to which use of the additive

(i) increases exposure to components of the additive itself or to combustion byproducts of the additive (e.g., the metal based additives or MTBE), and the toxicity of those substances at ambient levels;

(ii) decreases or increases vehicle emissions, which can improve or worsen ambient air pollution (e.g., a change in the emission of precursors of ozone, or a change in certain air toxics); and

(iii) reduces the content of other components of gasoline that are known to have adverse health effects.

252. This section focuses on what is or is not known about the health effects of the additives themselves, and of any significant expected emissions resulting from combustion of the additives. This assessment aims to place what is known about the additives within the context of the effects of the broader emissions from the fuel to which they are added.

1. Metallic Additives

a. Lead Alkyls: TEL and TML

253. Lead was widely used as an octane-enhancing additive for gasoline but is now almost entirely phased out because of its effects on health. Other metallic additives have been proposed or are in use in gasoline to fill the void left by the elimination of lead. Two major gasoline additives are ferrocene and MMT.

254. The growing body of research on the adverse health impacts of low-level concentrations of lead caused the US EPA in 1985 to reduce the maximum allowable lead content in leaded gasoline to 0.026 grams per liter. Subsequent studies, such as one in which 249 children were monitored from birth to 2 years of age, found that those with prenatal umbilical-cord blood lead levels at or above 10 micrograms per deciliter consistently scored lower on standard intelligence tests than those with lower concentrations. In a recent 5-year study of 172 children, with the support of the US National Institute of Environmental Health Sciences, researchers from the

University of Rochester, Cincinnati Children's Hospital Medical Center, and Cornell University demonstrated without a doubt that lead causes intellectual impairment at low levels. Further data emphasized that there is no threshold value, or safe level of lead exposure.[34]

255. Multiple analyses performed by Schwartz et al.,[35] confirm that each microgram per deciliter of blood lead concentration is associated with a reduction in intelligence quotient (IQ) of 0.25 points at these levels of exposure. These and other studies show that there is no threshold blood lead level below which cognitive effects are not seen. In addition, the effects of losing IQ points are greater in children with low IQ scores than those with higher scores.[36]

b. Ferrocene

256. There is extensive literature on the occupational effects of exposure to ferrocene at levels much higher than ambient levels expected from use of the substance as a fuel additive. Several research investigations and assessments of the substance's potential effects as a fuel additive have been made, including most notably

(i) A 13-week inhalation study in which rats and mice were exposed to ferrocene vapor concentrations of 3, 10, and 30 mg per cubic meter (0.39, 1.3, and 3.9 ppm). No changes in respiratory function, lung biochemistry, inflammation markers, or blood parameters were observed. The most prominent findings were epithelial lesions in the nasal cavity, which were seen in all animals, which showed a dose-dependent severity, and which suggested that ferrous iron is released inside the cells and causes a form of oxidative stress (i.e., lipid peroxidation of cellular membranes or formation of hydroxide radicals that react with cellular components [deoxyribonucleic acid and protein].[37]

(ii) The Health Council of the Netherlands, in reviewing the literature to make a recommendation for occupational limits, concluded that ferrocene did not induce mutations in several mutagenicity assays such as *S. typhimurium*, *D. melanogaster* after feeding (sex-linked recessive lethal assay), and mouse lymphoma cells (with metabolic activation) or chromosome aberrations, but was positive in a mutation assay in mouse lymphoma cells in the absence of a metabolic activating system, and, after injection, in a sex-linked recessive lethal assay and a heritable translocation assay in *D. melanogaster*.[38]

(iii) A longer-term exposure study done at the Fraunhofer Institute, in Hanover, Germany, compared emissions from a commercial diesel fuel containing 30 ppm

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[34] Canfield, R.L., C. R. Henderson Jr., D. A. Cory-Slechta, C. Cox, T. A. Jusko, and B. P. Lanphear. 2003. Intellectual Impairment in Children with Blood Lead Concentrations below 10 micrograms per deciliter. *New England Journal of Medicine*. 348(16): 1517-26.

[35] Schwartz, Joel, Philip J. Landrigan, Clyde B. Schechter, Jeffrey M. Lipton, and Marianne C. Fahs. 2002. Environmental Pollutants and Disease in American Children: Estimates of Morbidity, Mortality, and Costs for Lead Poisoning, Asthma, Cancer, and Developmental Disabilities. (Children's Health Articles). *Environmental Health Perspectives* 110: 721-28. Available: http://www.ehponline.org/docs/2002/110p721-728landrigan/abstract.html

[36] Fewtrell, Lorna, Rachel Kaufmann, and Annette Prüss-Üstün. 2003. Lead: Assessing the Environmental Burden of Disease at National and Local Levels. *Environmental Burden of Disease Series, No. 2*. Geneva: WHO. Available: http://www.who.int/quantifying_ehimpacts/publications/9241546107/en/

[37] Nikula, K. J., J. D. Sun, E. B. Barr, et al. 1993. Thirteen-Week Repeated Inhalation Exposure of F344/N Rats and B6C3F1 Mice to Ferrocene. *Fundamental and Applied Toxicology* 21: 127-39. Available: http://toxsci.oxfordjournals.org/cgi/content/abstract/21/2/127

[38] Health Council of the Netherlands: Committee on Updating of Occupational Exposure Limits. 2002. *Dicyclopentadienyl Iron (ferrocene): Health-based Reassessment of Current Administrative Occupational Exposure Limits in the Netherlands.* The Hague: Health Council of the Netherlands.

ferrocene with a fuel not containing ferrocene. This work involved chemical and physical characterization of exhaust, studies of exhaust fractions in in-vitro mutagenicity and cytotoxicity assays, and animal inhalation studies of chronic toxicity and carcinogenicity. Both mammalian (hamster lung cell line) and bacterial test systems (Ames test for mutagenicity) were used, and under the testing conditions used, ferrocene did not affect the cytotoxicity or mutagenicity (in four tester strains of Salmonella) of exhaust. Whole animal testing involved exposure of rats to the highest technically feasible exhaust concentrations (a 1:20 dilution of exhaust), a 1:40 dilution, and a clean air control. Animals exposed to exhaust from ferrocene-containing fuel did not respond differently than those exposed to fuels not containing ferrocene. No toxic effects were observed after 24-30 months.[39]

257. Based on its own review of this data, the CARB concluded in 2003 that

> Ferrocene has relatively low toxicity. The EU requirements also include it in its lowest toxicity class. There is no evidence of carcinogenicity or neurotoxic effects. Emission testing showed no general trends beyond an increase in iron in the exhaust, and chronic exposure studies showed no significant effect on subjects.[40]

258. The investigation and analysis of the health effects associated with ferrocene have, however, been less stringent than other, more widely used additives. Ferrocene is not approved by the US EPA because it has not been subjected to the US EPA's Tier 2 additive health effects evaluation required for gasoline additives. MTBE, ethanol, and MMT have been evaluated (or are in the process of being evaluated) through this approach.

c. MMT

259. Manganese is well understood to be a serious toxicant at very high levels of exposure (e.g., in certain occupations) where it can cause a neurologic disease known as manganism (a relative of Parkinson's disease) if inhaled. There is a growing body of literature on the health effects of exposure to manganese, and of MMT specifically, from natural, industrial, and mobile sources at ambient levels, as well as an emerging literature of population studies of potential effects.[41] This literature indicates that there are potential health risks of lower level exposure,

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[39] Fraunhofer Institut für Toxikologie and Aerosolforschung. 1996. *Investigation of Otto Engine Exhaust Resulting from the Combustion of Fuel with Added Ferrocene*. Hannover

[40] CARB. 2003. *Proposed Control Measure for Diesel Particulate Matter from On-Road Heavy-Duty Diesel-Fueled Residential and Commercial Solid Waste Collection Vehicle Diesel Engines*. California, U.S. Air Resources Board 2003

[41] Please see (i) Dobson, A. W., K. M. Erikson, and M. Aschner. 2004. Manganese Neurotoxicity. *Annals of the New York Academy of Sciences* 1012: 115–128; (ii) Tjälve, H., J. Henriksson, J. Tallkvist, B. S. Larsson, and N. G. Lindquist. 1996. Uptake of Manganese and Cadmium from the Nasal Mucosa into the Central Nervous System via the Olfactory Pathways in Rats. *Pharmacology & Toxicology* 79: 347-56; (iii) Elder, A., R. Gelein, V. Silva, T. Feikert, L. Opanashuk, J. Carter, R. Potter, A. Maynard, Y. Ito, J. Finkelstein, and G. Oberdörster. 2006. Translocation of Inhaled Ultrafine Manganese Oxide Particles to the Central Nervous System. *Environmental Health Perspectives* 114: 1172–78; (iv) Mena, I., K. Horiuchi, K. Burke, and G. C. Cotzias. 1969. Chronic Manganese Poisoning. Individual Susceptibility and Absorption of Iron. *Neurology* 19(10): 1000-06; (v) Zayed, J. 2001. Use of MMT in Canadian Gasoline: Health and Environmental Issues. *American Journal of Industrial Medicine* 39: 425-33; (vi) Bouchard, M., D. Mergler, M. Baldwin, M. Panisset, R. Bowler, and H. A. Roels. 2007. Neurobehavioral Functioning after Cessation of Manganese Exposure: A Follow-up after 14 Years. *American Journal of Industrial Medicine* 50(11): 831-40; (vii) Lucchini, R., E. Albini, L. Benedetti, S. Borghesi, R. Coccaglio, E. C. Malara, G. Parrinello, S. Garattini, S. Resola, and L. Alessio. 2007. High Prevalence of Parkinsonian

and this exposure continues to be the subject of health research. Based on the health concerns already identified, participants in a workshop convened by the Scientific Committees on Neurotoxicology and Psychophysiology and Toxicology of Metals of the International Commission on Occupational Health recently published their conclusion that, “The addition of organic manganese compounds to gasoline should be halted immediately in all nations.”[42]

260. Public agencies in some developed countries have reviewed the use of MMT. Most recently, the Australian National Industrial Chemicals Notification Section in 2003 reviewed the literature relating to MMT and noted that “MMT is highly toxic to aquatic organisms,” is highly toxic in animals and humans, and that accidental ingestion, especially from aftermarket additives, of MMT “represent[s] a significant acute health risk to children.” The report concluded that at the levels expected to be used—based on maintaining the relatively low use of MMT through the advanced fuel quality control systems in place in Australia—the risk would not appear to be significant.[43] Comparable fuel quality control systems are not in place in Asian countries.

261. The Health Effects Institute recently summarized some of the 2004 study by Yokel and Crossgrove[44]—when it noted, “There is a large body of evidence that (1) under certain circumstances, manganese can accumulate in the brain,[45] (2) chronic exposure can cause irreversible neurotoxic damage over a lifetime of exposure, (3) manganese may cause neurobehavioral effects at relatively low doses,[46] and (4) these effects follow inhalation of manganese-containing particles (neurotoxic effect of dietary manganese are much more rare) (ATSDR 2000).”

262. The US Clean Air Act requires testing of motor fuels and additives. US EPA has required the manufacturer of MMT to perform testing to help fill data gaps and potentially provide information that would result in a more definitive risk evaluation of MMT. This testing included

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Disorders Associated to Manganese Exposure in the Vicinities of Ferroalloy Industries. *American Journal of Industrial Medicine* 50(11): 788-800; (viii) Smith, Donald, Roberto Gwiazda, Rosemarie Bowler, Harry Roels, Robert Park, Christopher Taicher, and Roberto Lucchini. 2007. Biomarkers of Mn Exposure in Humans. *American Journal of Industrial Medicine* 50(11): 801-11; (ix) Vezér, T., A. Kurunczi, M. Náray, A. Papp, and L. Nagymajtényi. 2007. Behavioral Effects of Subchronic Inorganic Manganese Exposure in Rats. *American Journal of Industrial Medicine* 50(11): 841-52; and (x) US EPA Comments on the Gasoline Additive MMT (Methylcyclopentadienyl manganese tricarbonyl). Available: http://www.epa.gov/otaq/regs/fuels/ additive/mmt_cmts.htm

[42] Landrigan, Philip, Monica Nordberg, Roberto Lucchini, Gunnar Nordberg, Philippe Grandjean, Anders Iregren, and Lorenzo Alessio. 2006. The Declaration of Brescia on Prevention of the Neurotoxicity of Metals. *American Journal of Industrial Medicine* 50(10):709-11. Available: http://dx.doi.org/10.1002/ajim.20404 and http://www.collegiumramazzini.org/download/Declaration_of_Brescia_August_2006.pdf

[43] National Industrial Chemicals Notification and Assessment Scheme. 2003. *Methylcyclopentadienyl Manganese Tricarbonyl (MMT) Priority Existing Chemical Assessment Report No. 24*. Sydney: National Industrial Chemicals Notification and Assessment Scheme, Department of Health and Ageing

[44] Yokel, Robert A., and Janelle S. Crossgrove. 2004. *Manganese Toxicokinetics at the Blood–Brain Barrier*. *Research Report 119*. Boston: Health Effects Institute (HEI).

[45] Please see (i) Hauser, R. A., T. A. Zesiewicz, C. Martinez, A. S. Rosemurgy, and C. W. Olanow. 1996. Blood Manganese Correlates with Brain Magnetic Resonance Imaging Changes in Patients with Liver Disease. *Canadian Journal of Neurological Science* 23(2): 95-98; and (ii) Lucchini, R., E. Albini, D. Placidi, R. Gasparotti, M. G. Pigozzi, G. Montani, and L. Alessio. 2000. Brain Magnetic Resonance Imaging and Manganese Exposure. *Neurotoxicology* 21(5): 769-75.

[46] Roels, H. A., P. Ghyselen, J. P. Buchet, E. Ceulemans, and R. R. Lauwerys. 1992. Assessment of the Permissible Exposure Level to Manganese in Workers Exposed to Manganese Dioxide Dust. *British Journal of Industrial Medicine* 49(1): 25-34.

three health pharmacokinetic studies and one emission characterization study.[47] In addition to the already completed tests, the manufacturer is developing physiologically-based pharmacokinetic models for manganese derived from data generated from the completed testing. The manufacturer anticipates that these models will be completed in 2008. After submission of this additional information, US EPA will study the results and may then be able to refine its risk evaluation or may ask for further testing based upon the results of the submitted testing and resulting model now being developed, as well as upon any other available data. With funding from the manufacturer, the Research Triangle Institute also completed a study of manganese exposures in Toronto, Canada, where MMT had been used extensively.[48] US EPA is also evaluating this study to determine what impact it might have on any evaluation of risk associated with use of MMT. In the meantime, more than 99% of gasoline sold in the US contains no MMT.

263. In its draft report on the proposal for a directive of the European Parliament and of the Council amending Directive 98/70/EC as regards the specification of petrol, diesel, and gasoil, the Committee on the Environment, Public Health and Food Safety of the European Parliament proposed to amend Article 8a (Directive 98/70/EC). Existing text, which reads, "The Commission shall continue to develop a suitable test methodology concerning the use of metallic additives in fuel," would be amended to read: "Use of the metallic additive MMT in fuel shall be prohibited from 1 January 2010 onwards. The Commission shall develop a test methodology concerning the metallic additives other than MMT." [49]

264. Given the importance of the potential health risk at lower level exposures to MMT, Health Canada is finalizing an extensive risk assessment of manganese at ambient levels, based on the health impacts literature. In draft form, the report proposes a new reference concentration for manganese in air to replace the level established in 1994. This assessment is the most comprehensive one to date of the latest literature on potential effects of exposure to manganese at ambient levels from a variety of sources. In addition, it identifies gaps in current understanding and will serve as an important reference on this literature. The draft recommendations published for review propose that the new Health Canada reference concentration for inhaled manganese should be lowered to 0.05 micrograms per cubic meter in PM_{10}. [50] The draft report indicates a heightened concern for much lower ambient levels of manganese, raising concerns for adding any source of additional manganese. The recommended reference concentration would bring the Canadian standard in line with that of US EPA, which has set the most stringent current reference concentration in the world.

2. Oxygenates

265. The primary motor vehicle emissions potentially affected by adding oxygenates are CO and certain air toxics. In addition to helping to reduce CO, which is known to have effects on the blood and heart, adding oxygenates also appears to reduce benzene and toluene emissions

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[47] Completed final reports for all of these studies have been submitted to US EPA and are to be found in the Federal Docket Management System (FDMS) at www.regulations.gov, identified by docket number EPA-HQ-OAR-2004-0074. A number of these studies have also been published in the peer-reviewed literature.

[48] Pellizzari, E. D., R. E. Mason, C. A. Clayton, K. W. Thomas, S. Cooper, L. Piper, C. Rodes, M. Goldberg, J. Roberts, and L. Michael. 1998. Final Report - Manganese Exposure Study (Toronto). *Analytical and Chemical Sciences*. Durham: Research Triangle Institute.

[49] European Parliament, Committee on the Environment, Public Health and Food Safety, 2007/0019(COD).

[50] Wood, Grace, and Marika Egyed. 1994. *Risk Assessment for the Combustion Products of Methylcyclopentadienyl Manganese Tricarbonyl (MMT) in Gasoline.* Health Canada: Environmental Health Directorate.

and an increase in formaldehyde and acetaldehyde emissions. The final effect depends on the operation of the exhaust gas catalyst, in which different air toxics are affected differently.[51] Additionally, there are uncertainties in estimating personal exposure to each of the air toxics and in projecting the carcinogenic risk from each for humans.

a. Ethanol

266. The health effects of ingested ethanol have been extensively investigated. Given that ethanol is formed naturally in the body at low levels, inhalation exposure to ethanol at the low levels that humans are likely to be exposed to it are generally not expected to cause injury. Questions have been raised, however, about the risks to potentially sensitive subpopulations.[52]

267. Increased use of ethanol will result in increases of certain atmospheric transformation products, such as peroxyacetyl nitrate and acetaldehyde, although the extent of such an increase will vary depending on the vehicle and fleet characteristics and the percentage of ethanol in the fuel. Peroxyacetyl nitrate, which has been shown to be mutagenic in cellular research, is a known toxin to plant life and a respiratory irritant to humans.[53] Acetaldehyde is a respiratory irritant at high levels of human exposure and is currently classified by US EPA as a probable human carcinogen.

268. Ethanol is far less likely itself to travel great distances in groundwater than ethers because it appears to be rapidly biodegraded in soil. However, there is some evidence that the preferential degradation of the ethanol may retard degradation of other components in gasoline, such as toluene, causing them to spread further than they otherwise would.[54]

269. Lastly, the addition of relatively small quantities of ethanol to traditional gasoline can increase the volatility of the fuel and the likelihood of increased evaporative emissions, particularly in the higher ambient temperatures prevalent in Asia. This increases the concentration of precursors of ozone, known to cause exacerbation of asthma and other respiratory symptoms, and recently associated with an increase in premature mortality. [55]

b. Methanol

270. Methanol occurs naturally in plants and animals, and humans regularly consume low doses of it in their diet. Despite its ubiquitous presence methanol is well understood to be toxic when ingested in sufficiently high amounts. Ingestion of methanol (usually in the form of wood alcohol or tainted alcoholic beverages) can result in metabolic acidosis, blindness, and even

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[51] Poulopoulos, S. G., D. P. Samaras, and C. J. Philippopoulos. 2001. Regulated and Unregulated Emissions from an Internal Combustion Engine Operating on Ethanol-Containing Fuels. *Atmospheric Environment* 35 (2001) 4399-4406. Available: http://dx.doi.org/10.1016/S1352-2310(01)00248-5

[52] HEI. 1996. *The Potential Health Effects of Oxygenates Added to Gasoline: A Review of the Current Literature*. Boston: HEI.

[53] Altshuller, A. P. 1993. PANs in the Atmosphere. *Journal of the Air and Waste Management Association* 43(9): 1221-30.

[54] US EPA. 1999a. *Achieving Clean Air and Clean Water: The Report of the Blue Ribbon Panel on Oxygenates in Gasoline*. Available: http://www.epa.gov/OMS/consumer/fuels/oxypanel/r99021.pdf

[55] US EPA. 2007. *Review of the National Ambient Air Quality Standards for Ozone: Policy Assessment of Scientific and Technical Information*. Available: http://www.epa.gov/ttn/naaqs/standards/ozone/data/2007_07_ozone_staff_paper.pdf and http://www.epa.gov/ttn/naaqs/standards/ozone/data/ 2007_07_o3sp_appendices.pdf

death.[56] The lethal methanol dose for humans is uncertain but appears to vary widely from 0.3 to 1 gram per kilogram of body weight.[57] Although it would not be the common route of exposure, increased use of methanol may increase risks of accidental poisoning from fuel cans and other sources.

271. Were methanol to be widely adopted as a fuel, environmental exposures would increase through ingestion of contaminated drinking water, inhalation of vapors from evaporative and other emissions, and dermal contact. Current concentrations of methanol in ambient air are very low, 1 to 30 parts per billion (ppb). Even inhaling substantially increased concentrations of methanol that might result from increased fuel use for short periods of time should not present a risk of direct methanol toxicity and poisoning. At the same time, little is known about the consequences of long-term inhalation of methanol vapors, especially in the susceptible populations of pregnant women and developing fetuses, where there is some evidence of effects, even at lower levels of exposure for the former. However, one of the most extensive investigations did not find evidence of such effects in either mothers or their newborns, although there was some evidence of wasting disease in the mothers.[58]

c. MTBE

272. Animal inhalation toxicity testing to date generally has not shown MTBE to have significant effects on the nervous, immune, and reproductive systems, or to be any more toxic than other components of gasoline. This includes extensive testing of MTBE alone and in combination with gasoline, in response to requirements of the US Clean Air Act. [59]

273. Limited data are available on which human populations might be sensitive to MTBE. In addition, effects attributed to MTBE alone have yet to be proven. Limited epidemiological data suggest greater attention should be given to the potential for increased symptom reporting among highly exposed workers (footnote 52).

274. The International Agency for Research on Cancer and the US National Institute of Environmental Health Sciences have indicated that adequate data are not presently available to suggest that MTBE is either a probable or known human carcinogen.[60]

275. MTBE is highly soluble in water and has contaminated drinking water supplies in some parts of the United States. However, the majority of the population is not expected to suffer ill

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[56] HEI. 1987. *Automotive Methanol Vapors and Human Health: An Evaluation of Existing Scientific Information and Issues for Future Research. A Special Report of the Institute's Health Research Committee.* Boston: HEI.

[57] International Programme on Chemical Safety. 1997. *Environmental Health Criteria 196: Methanol.* Geneva: WHO.

[58] HEI. 1999. Reproductive *and Offspring Developmental Effects Following Maternal Inhalation Exposure to Methanol in Nonhuman Primates, Research Report No. 89, Part I: Methanol Disposition and Reproductive Toxicity in Adult Females, Part II: Developmental Effects in Infants Exposed Prenatally to Methanol*. Boston: HEI.

[59] Please see (i) Gray T. M., K. P. Hazelden, D. R. Steup, J. P. O'Callaghan, G. M. Hoffman, and L. G. Roberts. 2004. Inhalation Toxicity Of Gasoline and Fuel Oxygenates - Reproductive Toxicity Assessment. *Toxicologist* 78(1-S): 146; (ii) O'Callaghan, J. P., C. M. Felton, B. K. Mutnansky, and W. C. Daughtrey. 2004. Inhalation Toxicity Of Gasoline and Fuel Oxygenates: Neurotoxicity. *Toxicologist* 78 (S-1): 146; and (iii) White, K. L., V. L. Peachee, S. R. Armstrong, and L. E. Twerdok. 2004. Inhalation Toxicity of Gasoline & Fuel Oxygenate: Immunotoxicity. *Toxicologist* 78 (S-1): 148.

[60] Please see (i) Office of Science and Technology Policy, National Science and Technology Council. 1997. *Interagency Assessment of Oxygenated Fuels*; (ii) US EPA. 1997. *Drinking Water Advisory: Consumer Acceptability Advice and Health Effects Analysis on Methyl Tertiary-Butyl Ether (MtBE)*. Available: http://www.epa.gov/waterscience/criteria/ drinking/mtbe.pdf; (iii) National Research Council. 1996. *Toxicological and Performance Aspects of Oxygenated Motor Vehicle Fuels.* Washington, DC

effects from drinking water containing MTBE at or below the taste and odor levels identified in the US EPA's Drinking Water Advisory (20 to 40 micrograms per liter) (footnote 60[ii]). The turpentine-like taste and odor of MTBE, however, can make such drinking water unacceptable to the consumer.

276. Overall, experts in the United States and the EU have concluded that the addition of MTBE to fuel does not add significantly to the risk already present from existing components of gasoline.[61] In addition, to the extent that MTBE reaches water supplies, the odor and taste of any significant contamination is likely to alert users before they have ingested large quantities.

d. ETBE and TAME

277. Toxicity testing of ETBE and TAME has not been as extensive as that for MTBE. Recent expanded testing of these substances, both alone and with gasoline, performed in response to requirements of the US Clean Air Act (footnote 59), has found few effects, with those found appearing to be similar to those found for MTBE.

E. Effects of Octane-enhancing Additives on Vehicle Performance and Emissions

1. Metallic Additives

278. In its Worldwide Fuel Charter, the automotive industry states that

> Today's vehicles employ sophisticated emission control equipment such as three-way catalysts and exhaust gas oxygen sensors to provide precise closed-loop control. These systems must be kept in optimal condition to maintain low emissions for the lifetime of the vehicle. Ash-forming (metal-containing) additives can adversely affect the operation of catalysts and other components, such as oxygen sensors, in an irreversible way that increases emissions. Thus, high-quality gasoline should be used and ash-forming additives must be avoided (footnote 27).

The industry's primary concern about metal additives is to protect the long-term, in-use, effectiveness of exhaust gas post-treatment systems, OBD sensors, and engine components that are essential to maintain low emissions from the vehicle. To this end, the ACEA, among others, has recommended a ban on the use of metallic fuel additives in commercial fuel.[62]

a. Lead Alkyls: TEL and TML

279. Even slight lead contamination can permanently and drastically reduce the effectiveness of catalytic converters and oxygen sensors, causing a substantial increase in vehicle emissions. Nevertheless, it was the growing body of research showing the dangers of low-level concentrations of lead that led in most countries to a complete ban on the addition of lead additives to on-road gasoline.

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[61] Please see (i) HEI. 1996. *The Potential Health Effects of Oxygenates Added to Gasoline: A Review of the Current Literature*. Boston: HEI; (ii) European Union. 2002. *Risk Assessment Report: TERT-BUTYL METHYL ETHER. Final Report. CAS No: 1634-04-4, EINECS No: 216-653-1*. Finland. Available: http://ecb.jrc.it/DOCUMENTS/Existing-Chemicals/RISK_ASSESSMENT/REPORT/mtbereport313.pdf

[62] ACEA's response to the fuel directive's proposed changes is available at http://forum.europa.eu.int/Public/irc/env/fuel_quality/library?l=/stakeholder_2005/stakeholder_comments/acea_responsepdf/_EN_1.0_&a=d

b. Ferrocene

280. When combusted, ferrocene forms ferric oxides (also known as jeweler's rouge) which is a fine abrasive. Early studies of ferrocene showed excessive piston ring, cylinder bore, and camshaft engine wear at the concentrations investigated. Recent studies by the automotive industry at lower iron concentrations have shown premature spark plug failures at the current recommended concentration of 30 ppm (9 ppm iron). Concern has also been expressed that ferric oxide, or rust, will act as a physical barrier on oxygen sensors and exhaust catalyst surfaces, and may possibly cause catalyst plugging in modern vehicles.[63]

281. Limited testing has shown that the use of ferrocene as a fuel additive causes iron oxide deposits to adhere to the combustion chamber, spark plugs, and exhaust pipe, and that an abnormal electrical discharge pattern is provoked in spark plugs operating at high temperatures. Iron (II, III) oxide, or magnetite, is changed into ferric oxide under high temperatures. Discharge current flows in iron oxides containing ferric oxide because the conductivity of ferric oxide increases at high temperatures. These results indicate that adding ferrocene decreases the insulation resistance of spark plugs and increases fuel consumption, exhaust emissions, exhaust gas temperature, and irregular electrical discharge.[64]

282. There is also concern that iron oxide acts as a physical barrier between the catalyst/oxygen sensor and the exhaust gases, and leads to erosion and plugging of the catalyst, which negates its ability to treat the engine's exhaust emissions (footnote 27). These deposits can physically block channels of the catalyst, reducing the active surface area and increasing the velocity of the exhaust gas through the catalyst, and consequently reduce NO_X conversion, which is very sensitive to this parameter.

c. MMT

i. Vehicles Equipped with Emission Control Systems

283. MMT was first commercialized in 1959 and has been used in gasoline by itself and in combination with lead alkyls. The 1977 amendments to the US Clean Air Act banned the use of manganese antiknock additives in unleaded gasoline unless US EPA granted a waiver. In 1996, after several waiver requests and court actions by the manufacturer, the courts ordered the US EPA to grant a waiver for MMT.[65] Its use is limited to a maximum of 8.2 milligrams per liter (footnote 63), but less than 1% of the gasoline in the United States currently contains MMT.

284. Gasoline containing MMT can leave significant red-orange deposits on spark plugs, catalytic converters, oxygen sensors, and combustion chamber walls. According to the Association of European catalyst manufacturers,[66] it appears that MMT interacts with the catalyst leaving deposits of oxidized manganese. These deposits can physically block channels

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[63] Chevron. Undated. *Motor Gasolines Technical Review*. Available: https://www.chevron.com/products/ourfuels/prodserv/fuels/documents/Motor_Fuels_Tch_Rvw_complete.pdf

[64] Atsushi Kameoka - Japan Automobile Research Institute. 2006. *Influence of Ferrocene on Engine and Vehicle Performance*. Available: http://www.sae.org/technical/papers/2006-01-3448

[65] The court ruling was influenced by an argument that US EPA was not allowed to consider health risks in considering the request for a waiver.

[66] European Commission Directorate General Joint Research Centre (JRC) Working Group on Metallic Additives. 2004. Durability Testing. In draft minutes of the meeting held at the Directorate General Environment office, 6 May. Brussels.

of the catalyst, reducing the active surface area and increasing the velocity of the exhaust gas through the catalyst, and consequently reducing NO_X conversion, which is very sensitive to this parameter.[67] CO and HC conversion rates over the catalyst are in general much less affected by this phenomenon. The MMT can have other effects on the engine, but the interaction always results in the formation of deposits.

285. In 2002, automobile manufacturers completed a multi-year study of the impact of MMT on low emission vehicles. They found that after 160,000 km, the use of MMT significantly increased non-methane organic gases, CO, and NO_X emissions from the fleet. MMT also decreased fuel economy in the first 160,000 km by, on average, about 0.2 km per liter. Elsewhere, the study concluded that HC emissions also increased in the first 80,000 km for earlier model vehicles equipped with Tier 1 emission control technology. There were also reports of plugging in high-density honeycomb (brick) catalyst systems with MMT.[68] In addition, ACEA has reported that MMT can prevent the OBD systems from identifying the failed catalytic converter. ACEA states that the "presence of MMT in the system can cause a false reading by the OBD system, potentially allowing a failed catalyst to go unnoticed and unrepaired." [69]

ii. Vehicles without Emission Control Systems

286. MMT has been used without problems in vehicles not equipped with modern three-way catalytic converters, including pre-1981 federally certified cars in the United States. The possible detrimental effect on engines has not been an issue in those vehicles. However, the automobile manufacturers oppose the use of MMT in all gasoline because of concerns that in practice it will be used detrimentally in vehicles equipped with three-way catalysts and oxygen sensors. Maintaining separate fuel supplies is difficult and expensive. Steps would need to be taken to reduce the risk of misfueling, including legislating larger-diameter dispensing nozzles in the gas stations that cannot enter narrow filler-necks for modern emission-controlled vehicles. This technique was used in the United States during the period when both leaded and unleaded gasoline were available. However, during that time, a large number of vehicles were misfueled, destroying a large number of catalysts and leading to a substantial increase in emissions.

287. Many Asian countries will adopt cleaner vehicle emission standards in the coming years, which will require that vehicles are equipped with catalytic converters and also oxygen sensors. At the same time, many old vehicles will remain on the road without catalytic converters or oxygen sensors. It is not realistic to expect that Asian countries will be able to have separated

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[67] Please see (i) Schindler, K. P. - Volkswagen AG. 2004. *Impact of MMT on Vehicle Emission Performance*. Presented at Asian Vehicle Emission Control Conference 2004 (AVECC 2004), Beijing, 27-29 April. Available: http://www.meca.org/galleries/default-file/Schindler.pdf; and (ii) Benson, Jack D. - AFE Consulting Services, Inc., and Gregory J. Dana - Alliance of Automobile Manufacturers. *The Impact of MMT Gasoline Additive on Exhaust Emissions and Fuel Economy of Low Emission Vehicles (Lev).* Available: http://www.sae.org/technical/papers/2002-01-2894

[68] A systematic study involving swapping of parts between two Fords from the Alliance study, one run on clear fuel and the other on MMT containing fuel was undertaken, and the results have been presented in: McCabe, R. W., D. Dicicco, G. Guo, and C. P. Hubbard. 2004. *Effects of MmtSr Fuel Additive on Emission System Components: Comparison of Clear- and MmtSr-Fueled Escort Vehicles From the Alliance Study*. Available: http://www.sae.org/technical/papers/2004-01-1084; and Boone, William P., Carolyn Hubbard, Richard E. Solfis, Yl Ding, and Ann E. Chen. 2005. *Effect of MmtSr Fuel Additive on Emission System Components: Detailed Parts Analysis from Clear- and MmtSr-Fuel Fueled Escort Vehicles from the Alliance Study*. Available: http://www.sae.org/technical/papers/2005-01-1108. The manufacturer of MMT has argued that it has no negative effects on vehicle performance and emissions.

[69] ACEA. 2001. *ACEA Position on Metal Based Additives*. Available: http://www.unece.org/trans/doc/2002/wp29grpe/TRANS-WP29-GRPE-43-inf15.pdf

fuel supply systems; thus, it is important to opt for the fuel specifications that will optimize the air quality benefits of the advanced emission control devices. This will require using ultra low sulfur fuels, as well as avoiding the use of metallic additives that can harm catalysts and oxygen sensors.

2. Oxygenates

288. The 1977 amendments to the US Clean Air Act specified and controlled the use of oxygenates to ensure that they would not damage vehicle emission control systems and lead to failures that could increase emissions.

289. The US EPA, through its "substantially similar" provisions, allows MTBE, ethanol, TAME, and ETBE (but not methanol) to be blended into gasoline up to a concentration that would result in 2.7% oxygen by mass in the blend, which equates to 15.0%, 10.0%, 17.1%, and 16.6% by volume, respectively. The US EPA also created a process by which a waiver could be granted for an oxygenate recipe that the applicant had demonstrated would not cause or contribute to the failure of any emission control device or system.

290. Methanol is an oxygenate that can cause corrosion of metallic components of fuel systems and the degradation of plastics and elastomers (footnote 27). It is not permitted in the United States other than at low concentration with cosolvents (up to 0.3% by volume as a de-icer, and in special circumstances it is allowed to be used with other aliphatic alcohols).

291. Oxygenated gasoline is required in some parts of the United States during winter to reduce vehicle CO emissions. The use of oxygenates in reformulated gasoline is required during the rest of the year to reduce ozone formation and toxic air contaminants. Approximately 10% of all the gasoline sold in the United States by 2001 contained ethanol, and over half of the blends contained 10% ethanol by volume, known as E10 (footnote 63). It is important to note that market for E85 (85% ethanol) is growing in the United States as more flexible fuel vehicles become available, and that over 1,000 fuel stations now dispense E85 in the United States.

292. Oxygenates may be used in other areas of the United States where they are not required as long as EPA's maximum concentration limits are observed. However, as oxygenates are generally more expensive than the gasoline they displace, it is only through regulation that ethanol was likely to be used near its concentration limit. The other oxygenates will be used at the lowest concentrations possible (1%–7% by volume) to achieve the desired octane rating, and only when the most economical solution is to add oxygenates.

293. In the EU, oxygenates may be used to a maximum 15% by volume for ethers, 5% by volume for ethanol, and 3% by volume for methanol.[70] In addition, the European Committee for Standardization EN 228 unleaded gasoline specification has set targets for each member state for the market share of biofuels. These targets will be based on the challenging benchmarks set by Directive 2003/30/EC: 2.00% market share by December 2005; 5.75% market share by December 2010.[71]

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[70] European Parliament and Council. 1998. *Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 Relating to the Quality of Petrol and Diesel Fuels and Amending Directive 93/12/EEC*. Available: http://eur-lex.europa.eu/LexUriServ/site/en/consleg/1998/L/ 01998L0070-20031120-en.pdf

[71] More stringent targets for biofuels are under consideration in the EU. A particularly contentious issue involves the actual impacts of the production of biofuels, from direct and indirect landuse conversion, on greenhouse gas emissions.

294. The Japanese Industrial Standards K 2202 allows MTBE only up to 7% volume maximum. Canada limits methanol to 0.3% volume, other oxygenates to 2.7% mass oxygen, and ethanol specifically to 3.7% mass oxygen (nominally, 10% volume ethanol). Brazil allows up to 24% volume ethanol because vehicles are calibrated to use this high level.

a. Effect of Oxygenates on Vehicle Exhaust Emissions

295. Adding oxygenates to gasoline generally influences vehicle emissions primarily by affecting the balance of fuel and air in the engine. If a vehicle, tuned to run on gasoline, is run on fuel containing an oxygenate without readjustment, the engine will receive a leaner mix as a result of the oxygen contained in the fuel, at least for non-catalyst equipped vehicles without electronic feedback controlled fuel systems such as carbureted cars and most two- and three-wheelers. The leaner oxygen-fuel ratio will tend to reduce CO and HC emissions, but in some cases at the expense of an increase in NO_X.

296. The effects of a change in fuel may not be as large for modern catalyst equipped vehicles with electronic feedback controlled fuel systems, where an oxygen sensor in the exhaust stream together with other engine management sensors optimize the air-fuel mixture into the engine and the ignition timing, as these systems will compensate for the change to some extent for changing fuel, except during the start and warm up periods and at full engine loads, when the vehicle's electronic control system may work in "open loop" mode without lambda regulation.

297. Table 4.2 summarizes the effect of oxygenates-gasoline blends in regulated emissions from modern cars.

Table 4.2: Effect of Oxygenates on Vehicle Emissions, when RVP Is Controlled and No RVP Increases Are Allowed

Compound	Effect of Oxygenates
CO	Significant decrease
HC	No effect or slight decrease
NO_X	No effect or small increase
CO_2	No effect or slight increase

CO = carbon monoxide, CO_2 = carbon dioxide, HC = hydrocarbons, NO_X = nitrogen oxides, RVP = Reid vapor pressure.
Source: European Fuel Oxygenates Association. Available: http://www.efoa.org

298. Some tests[72] have shown that the addition of alcohols to gasoline at 10% or higher blend ratios can reduce all three regulated emissions in vehicle fleets not equipped with closed loop

[72] Please see (i) SAE. 1996a. *Gasoline/Alcohol Blends: Exhaust Emissions, Performance and Burn-Rate in a Multi-Valve Production Engine*. Detroit: Society of Automotive Engineers. Available: http://www.sae.org/technical/papers/961988; and (ii) SAE. 1996b. *Federal Test Procedure Emissions Test Results from Ethanol Variable-Fuel Vehicle Chevrolet Luminas*. Detroit: Society of Automotive Engineers. Available: http://www.sae.org/technical/papers/961092

engine management systems where engines are typically operated lean, depending on the calibration of the engine. The extent of the reduction in emissions is expected to vary on the basis of the engines' air/fuel ratio control strategy. If a carburetor is set to provide a very fuel-rich mixture, fuel leaning might improve performance. Otherwise, fuel leaning can degrade driveability, depending upon the engine's calibration.

b. Air Quality Impacts of Other Oxygenates

299. In non-catalytic-converter equipped vehicles, the use of oxygenates in gasoline would be expected to produce additional emissions of formaldehydes and acetaldehydes when compared to non-oxygenated gasoline. MTBE and TAME would increase formaldehyde emissions, while ETBE and ethanol would increase emissions of acetaldehyde. In catalytic-converter equipped vehicles, however, the magnitude of the increase would depend upon the effectiveness of catalytic systems.[73]

300. Extensive emission tests[74] conducted with RFG containing MTBE, TAME, and ETBE have shown that the differences in regulated emissions, speciated HC, formaldehyde, and total particulates were generally insignificant when fuels containing biocomponents were compared to the RFG. The acetaldehyde emissions were higher for the fuels containing ETBE or ethanol than for the RFG. The differences in the particulate and semivolatile PAH emissions were low for these fuels.

301. Oxygenated gasoline gives lower fuel economy than conventional gasoline because the heating values of the oxygenates are lower than those of the hydrocarbons they displace. The percentage change in fuel economy is similar to the mass percent oxygen in the gasoline.

i. MTBE

302. The presence of oxygen within MTBE helps gasoline burn more completely, reducing tailpipe emissions from vehicles, which is especially beneficial in older cars and two- and three-wheelers.

303. MTBE's low vapor pressure is attractive because it contributes low-boiling quality to gasoline, a particularly desirable quality for low-speed performance in manual transmission vehicles. This characteristic also helps maintain the T50 standards, which are an important consideration for modern higher performance engines.

304. Because amounts of MTBE less than 31 milligrams of MTBE per kilogram of water (which equates to levels on the order of 5 ppb) affect the taste and odor of drinking water, it has been effectively banned in Australia and California, and is being phased out in the rest of the United States. In the aftermath of MTBE usage in the United States, stringent regulations were developed for underground storage tanks and leakage detection. In addition, it was necessary to determine the liability and financial responsibility for cleaning up contaminated ground water and leakages.

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[73] California Environmental Protection Agency. 1999. *Air Quality Impacts of the Use of Ethanol in California Reformulated Gasoline*. Air Resources Board. 1999. Available: http://www-erd.llnl.gov/ethanol/etohdoc/vol3/vol3.pdf

[74] Aakko, P., A. Jäntti, J. Pentikäinen, T. Honkanen, and L. Rantanen. 2002. *An Extensive Analysis of the Exhaust Emissions from Spark-Ignition Vehicles Using Fuels with Biocomponents*. Paper presented at Fisita World Autmotive Congress. 2-7 Jun 2002, Helsinki, Finland.

ii. Ethanol

305. The main advantage of adding ethanol to gasoline is its very high octane number.[75] Ethanol is soluble in gasoline; however, water contamination may lead to phase separation. The actual phase separation conditions are a function of ethanol content, temperature, and properties of the gasoline phase, but the effect is particularly marked at low ethanol concentrations. As there typically is a small amount of water in finished gasoline, the ethanol has to be transported separately from gasoline and mixed at the tanker prior to dispatch.

306. Ethanol has a higher heat of vaporization than ethers. Some of the degradation in driveability of gasoline oxygenated with ethanol can be attributed to the additional heat needed to vaporize the fuel (footnote 63).

307. There is a concern that the use of gasoline-ethanol blends increases the vehicle's evaporative emissions because blends of ethanol and gasoline can result in a disproportionate increase in the vapor pressure of the finished product.[76] The evaporative emissions are a function of RVP and ambient temperature. Thus, Asian countries where ambient temperatures are generally high should expect these effects of ethanol blending into gasoline to be much higher.

308. Even where only part of the gasoline contains ethanol, the mixing of fuel in the vehicle during refueling (e.g., gasoline with a 10% ethanol-blend at a given RVP and a non-ethanol blend of the same RVP)—the so called commingling effect—can increase the average RVP of all the fuel consumed by about 3.4 kPa,[77] and thus increase evaporative emissions from the entire fleet.

309. In a 1998 CARB report, based on the then average US vehicle fleet composition, the US EPA complex model estimated that high RVP gasoline containing 10% ethanol would increase the total HC for exhaust emissions by 3%, and by 40% for evaporative emissions.[78]

310. Permeation with ethanol is also a concern. In a study conducted in 2003–2004, the Coordinating Research Council, in cooperation with CARB, found higher permeation emissions when ethanol replaced MTBE as the test fuel oxygenate (both oxygenated fuels contained 2% oxygen by weight). The ethanol-blended fuel increased the average diurnal permeation emissions by 1.4 grams per day as compared to the MTBE fuel, and by 1.1 grams per day as compared to the non-oxygenated fuel. The study also confirmed previous estimates that

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[75] European Commission Directorate-General for Energy. 2000. *A Technical Study on Fuels Technology Related to the Auto-Oil II Programme - Final Report - Conventional Fuels*. Available: http://ec.europa.eu/energy/oil/fuels/doc/conventional_fuels_en.pdf

[76] Please see (i) Sierra Research, Inc. 2000. *Report No. SR00-01-01: Potential Evaporative Emission Impacts Associated with the Introduction of Ethanol-Gasoline Blends in California*; (ii) National Renewable Energy Laboratory. 2002. *Issues Associated with the Use of Higher Ethanol Blends (E17-E24)*; and (iii) Conservation of Clean Air and Water in Europe (CONCAWE). 2004. *Gasoline Volatility and Ethanol Effects on Hot and Cold Weather Driveability of Modern European Vehicles*, CONCAWE Report No. 3/04. Brussels.

[77] CARB. 1998a. *Comparison of the Effects of a Fully-Complying Gasoline Blend and a High RVP Ethanol Gasoline Blend on Exhaust and Evaporative Emissions*. California, Air Resources Board.

[78] CARB. 1998b. *Proposed Determination Pursuant to Health and Safety Code Section 48830(g) of the Ozone Forming Potential of Elevated RVP Gasoline Containing 10 Percent Ethanol*. California, Air Resources Board

permeation of these gasoline-ethanol blends doubles for each 10°C rise in temperature.[79] However, the CARB study indicated that when a higher ethanol blend is used in flexible fuel vehicle fuel systems (e.g., 85% ethanol), permeation emissions are lower.

311. Since the mid-1980s, automobile manufacturers have upgraded the material specifications used in their fuel system components at different times in different countries. Elastomers in older vehicles and low cost replacement parts may be sensitive to ethanol and high-aromatic gasoline, thus causing unintended leakages. Fuel system components used in other parts of the world may not be designed for use with oxygenated fuels.

iii. ETBE and TAME

312. Ethanol can also be used to produce ETBE, which is about 42% ethanol and is produced by processing renewable ethanol with isobutylene, a refinery byproduct. Global auto manufacturers and refiners prefer this route when they are required to utilize renewable fuels (footnote 27).

313. ETBE, like MTBE, can be used immediately and does not require changes to refining, pipeline and distribution operation, or automotive technology. Unlike ethanol, ETBE can be blended into the final gasoline right in the refinery and then be shipped to its point of sale through the traditional transportation pipeline. Blend volatility is not increased by ETBE.

314. In Europe, ETBE is becoming the preferred use of ethanol by both refiners and vehicle manufacturers. Bio-ethers are key tools to enable bio-ethanol market penetration and to meet the EU biofuel directive. Many MTBE units have today been converted to allow the use of either MTBE or ETBE dependent on their tax situation and raw material availability.[80]

315. Japan's Biomass Strategy incorporates a 2003 decision to allow for up to 3% blending of ethanol, and for up to 8% blending of ETBE. Japan supports the switch from MTBE to ETBE over widespread ethanol use mainly because of costs and logistics. There are currently four unused MTBE facilities in Japan that could return to producing ETBE. In addition, ETBE could relatively easily be used on a national scale, while ethanol blends would only be feasible locally or regionally. ETBE is still seen, however, to present possible environmental hazards, and the fuel industry must show it is taking countermeasures to reduce those potential impacts within about 2 years.[81]

316. TAME is produced by a process similar to that for ETBE, except from methanol and isoamylenes. It shares MTBE's excellent tolerance to water and requires no changes to the refining, pipeline and distribution operation, or automotive technology.

317. TAME's octane rating is approximately six points lower than MTBE and ETBE and has the lowest RVP and highest boiling point of the three (10 kPa and 86°C, respectively). TAME does not increase blend volatility in any way.

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[79] IDIADA. 2003. *Comparison of Vehicle Emissions at European Union Annual Average Temperatures from E0 and E5 Petrol*. IDIADA Report LM030411 (oppdragsgiver Abengoa Bioenergia). Available: http://biodiesel.pl/uploads/media/Comparison_of_vehicle_emissions_at_European_Union_annual_ave.pdf

[80] Asian Clean Fuels Association (ACFA). 2006. ACFA News Vol 4 Issue 8 (Nov/Dec 2006). Available: http://www.acfa.org.sg/newsletter.php?year=2006%23

[81] Fukuda, Hisao, Aaron Kingsbury, and Kakayu Obara. 2006. *Japan Bio-fuels Production Report 2006*. Available: http://www.fas.usda.gov/gainfiles/200605/146197881.pdf

318. TAME's oxygen content is the same as ETBE (15.66% by mass) and provides similar improvements in combustion and vehicle performance.

c. Comparative Characteristics of Principal Oxygenates

319. Table 4.3 summarizes the properties of oxygenates discussed above, along with the estimated values of RVP and boiling point.

Table 4.3: Characteristics of Principal Oxygenates

Oxygenate	(R+M)/2[a]	Blending RVP (kPa)	Boiling Point (ºC)	Oxygen Content (%)	Energy Content (MMBtu/l)	Max Allowed by US EPA	Max Allowed by EU
MTBE	114	55.2	55	18.2	24.7	15%	15%
Ethanol	120	124.1	78	34.8	20.1	10%	5%
TAME	105	17.2	86	15.7	26.6	2.7%[b]	15%
ETBE	112	27.6	72	15.7	25.2	2.7%[b]	15%
Methanol	116	344.7-413.7	65	49.9	15.0	2.75%[c]	3.0%

ºC = degrees Celsius, ETBE = Ethyl tertiary-butyl ether, EU = European Union, kPa = kilopascal, M = motor octane, MMBtu/gal = mega (or 10^6) British thermal units per liter, MTBE = Methyl tertiary-butyl ether, R = research octane, RVP = Reid vapor pressure, TAME = Tertiary amyl methyl ether, US EPA = US Environment Protection Agency.
[a] Octane values of oxygenates vary depending on the composition of the base gasoline.
[b] Weight % as oxygen.
[c] With equal volume of butanol.
Source: American Petroleum Institute. 2001. *Alcohols and Ethers: A Technical Assessment of Their Applications as Fuels and Fuel Components*. IHS; Hart Publications. *21st Century Refinery*; J. Courtis.

3. Summary of Effects of Octane-enhancing Additives on Emissions

320. Tables 4.4 and 4.5 summarize the impacts of metallic additives and oxygenates on emissions from light duty gasoline vehicles and two- and three-wheelers. The sources underlying this summary are cited in the relevant sections of this chapter.

Table 4.4: Impact of Octane-Enhancing Additives on Emissions from Light-Duty Vehicles

<table>
<tr><th>Additive</th><th>No Catalyst</th><th>Euro 1</th><th>Euro 2</th><th>Euro 3</th><th>Euro 4</th><th>Euro 5</th><th>Comments</th></tr>
<tr><td>Lead</td><td>HC increase, lead emissions</td><td colspan="5">CO, HC, NO_X all increase dramatically as catalyst destroyed plus lead emissions</td><td></td></tr>
<tr><td>MMT</td><td colspan="3">Manganese oxide emissions</td><td>Possible catalyst plugging plus manganese emissions</td><td colspan="2">Likely catalyst plugging plus manganese emissions</td><td>O_2 sensor and OBD may be damaged</td></tr>
<tr><td rowspan="2">Ferrocene</td><td colspan="3"></td><td>Possible catalyst plugging</td><td colspan="2">Likely catalyst plugging</td><td></td></tr>
<tr><td colspan="6">Deposits of iron oxides on combustion chamber, spark plugs. Can cause misfire in spark plugs operating at high temperatures. HC and Fuel consumption increase plus iron oxide emissions. Possible catalyst plugging</td><td>O_2 sensor and spark plugs may be damaged</td></tr>
<tr><td>MTBE
up to 15.0% vol (2.74% mass O_2)</td><td>Lower CO, HC, higher aldehydes</td><td colspan="5">Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems</td><td>Serious concerns over water contamination</td></tr>
<tr><td>ETBE
up to 17.1% vol (2.7% mass O_2)</td><td>Lower CO, HC, higher aldehydes</td><td colspan="5">Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems</td><td>Concerns over water contamination</td></tr>
<tr><td>TAME
up to 16.6% vol (2.7% mass O_2)</td><td>Lower CO, HC, higher aldehydes</td><td colspan="5">Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems</td><td>Concerns over water contamination</td></tr>
<tr><td>Ethanol
up to 10.0% vol (3.7% mass O_2)</td><td>Lower CO, HC, slight NO_{XX} increase (when above 2% oxygen content), higher aldehydes, potential effects on fuel system components particularly for older vehicles</td><td colspan="5">Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems</td><td>Increased evaporative emissions unless RVP adjusted, small fuel economy penalty</td></tr>
</table>

CO = carbon monoxide, ETBE = ethyl tertiary-butyl ether, HC = hydrocarbons, mg/l = milligram per liter, MMT = methylcyclopentadienyl manganese tricarbonyl, MTBE = methyl tertiary-butyl ether, NO_X = nitrogen oxides, O_2 = oxygen, OBD = on-board diagnostics, RVP = Reid vapor pressure, TAME = tertiary amyl methyl ether, % vol = percent by volume.

Source: Authors

Table 4.5: Impact of Octane-Enhancing Additives on Emissions from Two- and Three-Wheelers

Additive	No Catalyst	India 2005	Euro 3	India 2008	Taipei,China Stage 4	Comments
Lead	HC increase, lead emissions	CO, HC, NO_X all increase dramatically as catalyst destroyed plus lead emissions				
MMT	Manganese emissions	Possible catalyst plugging plus manganese emissions				O_2 sensor and OBD may be damaged
Ferrocene		Possible catalyst plugging				
	Deposits of iron oxides on combustion chamber, spark plugs. Can cause misfire in spark plugs operating at high temperatures. HC and fuel consumption increase plus iron emissions. Possible catalyst plugging					O_2 sensor and spark plugs may be damaged
MTBE up to 15.0% vol (2.74% mass O_2)	Lower CO, HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems				Serious concerns over water contamination
ETBE up to 17.1% vol (2.7% mass O_2)	Lower CO & HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems				Concerns over water contamination
TAME up to 16.6% vol (2.7% mass O_2)	Lower CO & HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems				Concerns over water contamination
Ethanol up to 10.0% vol (3.7% mass O_2)	Lower CO & HC, slight NO_X increase (when above 2% oxygen content), higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems				Increased evaporative emissions unless RVP adjusted, small fuel economy penalty. Potential effects on fuel system components, particularly for older vehicles; potential deposit issues

CO = carbon monoxide, ETBE = ethyl tertiary-butyl ether, HC = hydrocarbons, mg/l = milligram per liter, MMT = methylcyclopentadienyl manganese tricarbonyl, MTBE = methyl tertiary-butyl ether, NO_X = nitrogen oxides, O_2 = oxygen, OBD = on-board diagnostics, RVP = Reid vapor pressure, TAME = tertiary-amyl methyl ether, % vol = percent by volume.
Source: Authors

F. Effects of Octane-enhancing Additives on Refinery Processes

321. A refinery's ability to produce gasoline at the specified octane value for each grade is generally variable and a function of the refinery's complexity and configuration. As discussed above, gasoline is a blend of various refinery streams with different properties and different octane values. Table 4.6 provides an example of blend-stocks, simple hydrocarbons, oxygenates, and their main properties as used for gasoline production.

Table 4.6: Example of Blend-stocks Used for Gasoline Production

Blend-stock	% Gasoline Pool	Research Octane Number	(R+M)/2	Sulfur (ppm)	Aromatics (% vol)	Olefins (% vol)
Reformate	High	98	93	Low	71	0
Toluene	Med	124	118	0	100	0
FCC Light	Med	91	85	60	7	42
Xylene	Low	133	124	0	100	0
Ethanol	Low	120	110	Low	0	0
ETBE	Low	117	110	0	0	0
MTBE	Low	114	106	0	0	0
TAME	Low	111	105	0	0	0
Benzene	Low	99	95	0	100	0
Butane	Low	94	92	0	0	0
Alkylate	Low	91	90	Low	0	0
FCC Heavy	Low	89	84	300	40	13
Isomerate	Low	86	86	Low	0	0
Methanol	Very low	133	116	0	0	0

ETBE = ethyl tertiary-butyl ether, FCC = fuel catalytic cracking, M = motor octane, MTBE = methyl tertiary-butyl ether, ppm = parts per million, R = research octane, TAME = tertiary-amyl methyl ether, % vol = percent by volume.
Source: J. Courtis; Hart Publications. *21st Century Refinery*; United States Environmental Protection Agency. 1999b. *Implementer's Guide to Phasing Out Lead in Gasoline.* Available: http://www.epa.gov/oia/air/pdf/EPA_phase_out.pdf

322. To meet the octane requirements for each grade described in Table 4.6, refineries historically have produced gasoline by using the blend-stocks and additives described in the following sections.

1. Refinery-produced Hydrocarbons or Hydrocarbon Mixtures

323. As Table 4.6 indicates, reformate, alkylate, isomerate, and oxygenates have been the traditional components for most of the octane at the refinery. The ability of Asian refineries to use some of these blend-stocks is mixed based on current refinery configurations in Asia. In many parts of Asia, refinery upgrades and even new refineries are being planned to meet rising demand. The experience in the developed world provides a good opportunity to design refining processes to enhance octane without the need for additives.

324. Pure hydrocarbon streams such as benzene, toluene, and mixed xylenes, and their blends, are also produced at the refinery and could be used for octane enhancement. In addition, these blend-streams are also important petrochemical feedstocks and are exported to petrochemical facilities. Their use as octane agents at the refinery downgrades their economic value to the refiner because they are valued much more highly in the petrochemicals market. In addition, use of reformates and blend-streams for octane enhancement is constrained by the limits of aromatics.

325. Another compound that is part of the gasoline pool and has high octane value is butane. If higher levels of RVP are allowed, higher quantities of butane would find their way into the gasoline pool.

2. Metallic Additives

326. As described above, MMT and ferrocene have been used by refiners in some countries as an octane enhancement additive, especially in the past when concerns about health effects and the effects of such additives on vehicle performance and emissions were not as well understood as now. The use of metallic-based additives is attractive to refineries because of the lower cost, the ease of use, and the flexibility for adjusting octane. A small concentration of MMT or ferrocene added to the gasoline pool can satisfy some of the octane requirements. The use of MMT and ferrocene does not require special handling equipment, and it can be added to gasoline by the use of existing additive injection equipment. In addition, it does not affect any other gasoline properties.

3. Oxygenates

327. Because the mandate that required the use of oxygenates in the United States set standards only on the oxygen content and was oxygenate neutral, the refineries selected the least expensive option, which was MTBE. Small amounts of ethanol and TAME were originally used, but not ETBE. Some of the MTBE used were produced at the refineries from methanol and isobutylene, and some were purchased and imported to the refineries.

328. The advantage in using MTBE was that it was priced close to the price of gasoline, blended easily at the refinery, was widely available, and had been used extensively. However, water contamination issues have led to it now being banned in a number of countries.

329. Ethanol competes with MTBE for market position and is produced from agricultural feedstocks or biomass at agricultural locations. Ethanol's strong affinity to water makes the gasoline-ethanol mixture a difficult blend to transport through the pipeline system. As a result, ethanol is transported separately by rail or by tank truck in the fuel marketing and distribution system to various points where it is blended with gasoline. This need for downstream blending together with ethanol's effect on RVP make the logistics and the ability to control the properties of the final blend more problematic for the refinery.

330. TAME, another oxygenate, is also produced at the refinery from isoamylene and methanol. In the past, much of the TAME that was consumed was produced with MTBE and was used to supplement MTBE stocks in Europe.

331. ETBE is produced from ethanol and isobutylene at a significantly higher cost than that of either MTBE or ethanol. Refiners prefer ETBE, however, because it does not have the disadvantages of ethanol, such as affinity to water and RVP increases. Some refineries have explored the possibility of converting existing MTBE production facilities to ETBE production. ETBE is not yet available for purchase in the fuels markets, although some quantities are produced and used in the United States and the EU.[82]

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[82] Please see (i) Hart Energy Publishing. *21st Century Refinery*; (ii) US EPA. 1999. *Implementer's Guide to Phasing Out Lead in Gasoline*. Available: http://www.epa.gov/oia/air/pdf/EPA_phase_out.pdf; and (iii) J. Courtis.

332. Methanol is produced from natural gas and is available in the marketplace. Although it can provide significant octane increases, some auto manufactures recommend against blending it in gasoline.

G. Impacts of Changes in Gasoline Standards on Octane Number

333. The implementation of stricter gasoline standards in support of stricter vehicle emission standards can alter refinery processes, blend-stocks, and the properties of the blend-stocks used in the gasoline pool, thus affecting the octane balance at the refinery. In this context, Asian countries can benefit from the experience gained through two major regulatory programs: (i) the removal of lead, and (ii) the implementation of the Euro 4 fuel standards in the EU, or the Tier 2 gasoline standards in the United States.

1. Transition from Leaded to Unleaded

334. Although the removal of lead and the transition to unleaded gasoline has been successful in most countries, it has created an octane deficit in the range of 2-8 octane numbers. To increase octane, refineries generally have employed more of their reforming capacity, either by adding new reforming capacity, expanding and adding new hydrotreating capacity, or expanding the blending of some oxygenates. In some cases, refineries used octane-enhancing additives. Refineries in Asia, Australia, Canada and the United States, [83], and, to a limited extent, Europe used MMT for a quick transition from leaded to unleaded gasoline. In some cases, MMT was used as an integral part of the lead phase out strategy, and in others it was used on a limited basis to supplement the use of oxygenates and as an octane trimming agent in the blending of gasoline.

335. Although the various strategies among refineries depended upon individual refinery configuration, they were also affected by the availability and comparative costs of various high octane blend-stocks and oxygenates or metallic additives, and by the ease of transition from leaded to unleaded gasoline. This transition was generally quicker and less costly when assisted by the use of oxygenates, MMT, or both. Although some refiners later discontinued the use of MMT or of some oxygenates, they were still able to provide sufficient quantities of unleaded gasoline.

2. Transition to Euro 4 or US Tier 2 Fuel Standards

336. New fuel specifications required to meet Euro 4 or Tier 2 standards represent an additional challenge for the refinery's octane balance. Reducing sulfur content to meet Euro 4 fuel or Tier 2 standards requires deep hydrotreating for all or part of the FCC gasoline. Even with current advanced technologies, this may result in a potential octane penalty of 1 to 2 octane numbers depending on the specifics of the refinery. To reduce the levels of aromatics and benzene to the Euro 4 or Tier 2 standards, a refinery would have to reduce the severity of the reformer and possibly extract benzene from the gasoline pool.

337. RVP reductions will also affect octane levels. RVP is reduced as the amount of light compounds such as butanes or pentanes are reduced from the gasoline pool. These compounds have high octane values; thus their removal would reduce the octane of the pool.

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[83] California Energy Commission. 1998. *Supply and Cost of Alternatives to MTBE in Gasoline.*

338. Although smaller hydroskimming refineries that rely heavily on straight run gasoline would have less difficulty with the standards for olefins, aromatics, or sulfur, in the absence of a reformer, these refiners would have limited capacity to produce high octane components and would have to rely on imported blend-stocks to meet their interim needs. High octane blend-stocks with desirable properties, such as low aromatics, low sulfur, and low olefins, are not readily available in the fuels market. The principal low-cost options for refiners would be to import and use oxygenates (MTBE or ethanol) or to use metallic additives (MMT or ferrocene).

339. To meet the Euro 4 or Tier 2 fuel standards, many refineries would have to invest in the construction of new processes or in the expansion of existing processes. Some supplemental or additional processes or changes in process operations may be required to satisfy the resultant change in octane requirements. Various regulatory constraints, economics, the availability of capital, and the availability of refinery feedstocks would affect the implementation of such changes. Three main approaches can be taken.

a. Choose Ethanol and ETBE over MTBE or Metallic Additives

340. Refineries would need to implement an integrated refinery retrofit program in which both the Euro 4 or Tier 2 fuel standards and the octane targets would be met through process modifications. Under this scenario, no relaxation of Euro 4 or Tier 2 standards would be allowed, and refiners would be required to use high volumes of gasoline blend-stocks such as reformate, alkytale or isomerate, and ethanol or ETBE to produce gasoline. Some refiners would be required to invest in reforming capacity, although reformate use would be constrained because of the high levels of aromatics. Because alkylates and isomerates are not readily available in the fuels market, refineries would have to invest in the construction of alkylation and isomerization units, the size of which would be constrained by the availability of feedstocks at the refinery. The in-house production of ETBE is possible with necessary investments to convert existing MTBE facilities to ETBE production. The importation of ethanol would be an integral part of the refineries' strategy under this scenario.

341. This approach is relatively capital intensive. It is generally followed only where mandates for use of biocomponents are in place, and it could rely on the importation of either some feedstocks or some finished products. Notwithstanding the concerns about cost frequently expressed by refiners, it should be noted that the oil industry in the United States has been able to provide very clean, high quality, and low emission fuel that meets the performance requirements of the vehicle industry—including octane—without using MMT. At the same time, the industry is meeting new requirements for the reduction of sulfur, benzene, and other air toxics.[84]

b. Blend Oxygenates and Metallic Additives

342. Under this scenario, refineries may rely on capital investments, use oxygenates or metallic additives, or combine these approaches. Some EU countries use MTBE and ethanol, while others use different oxygenates and to a much lesser extent, metallic additives such as MMT. Canada's approach has been similar to that of the EU, although Canada has relied more on metallic additives such as MMT, given the absence of regulation on MMT there. Generally, in

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[84] Oge, Margo Tsirigotis. 2007. Personal communication from Director, Office of Transportation and Air Quality, US EPA. 5 March.

the EU where MTBE is allowed and widely used, capital investments to meet Euro 4 standards were less than investments required to meet Tier 2 standards in the United States.[85]

343. The absence of regulation limiting the use of oxygenates or of metallic additives allowed some refineries to meet the regulatory standards with less capital expenditures and greater flexibility. Nonetheless, refiners generally did not use metallic additives, and relied exclusively on process modifications, investments, or oxygenates to comply with the standards. Oxygenates and metallic additives are added as components to the gasoline pool and can be used by refiners as they need them. Refiners are guided primarily by regulations in their use of oxygenates and metallic additives, although price and supply are also important considerations.

c. Relax Some Euro 4 or US Tier 2 Fuel Specifications

344. A third scenario, one which did not occur either in the EU or the United States, would be to implement an integrated plan requiring only some of the gasoline properties specified in the Euro 4 or Tier 2 standards and relaxing some of the property standards. The highest priority could be given to maintaining a strict compliance with the sulfur content standard as sulfur is the most critical property for the performance of emission control systems.

345. The three most critical properties for maintaining octane balance are aromatics, olefins, and RVP. Relaxing the Euro 4 or Tier 2 standards for one or all of these properties would help to satisfy partially the octane needs. It would reduce capital investments, but it would also result in important air quality penalties. Increasing aromatics content would increase the amounts of benzene in the exhaust and potentially increase the overall hydrocarbon emissions. Increasing olefins content would result in higher levels of 1-3, butadiene in the exhaust and would increase the photochemical reactivity of the HC emissions, as olefins are much more photochemically reactive than other HC species. Increases in RVP would result in much higher evaporative HC emissions, which are critically important for Asian cities where ambient toxics and ozone are important air quality issues.

346. The relaxation of some properties has been discussed in some Asian countries. For example, Thailand considered and implemented a relaxation of both the RVP and the aromatics content standard. In Indonesia and the PRC, where a high olefins content gasoline is produced, there have been concerns about meeting the Euro 4 olefins content standard.[86] A number of Asian countries are considering the implementation of strict RVP standards.

3. Economics of the Various Options

347. It is difficult to determine the exact cost of octane replacement, as it would vary for each refinery, depend upon the refinery configuration, the types of processes that refinery would employ, and the availability and costs of critical blend-stock components and additives in the fuels market.

348. Small topping refineries are limited in their ability to comply with the Euro 4 standards while meeting octane needs without significant capital investments. These refineries lack

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[85] Please see (i) European Commission Directorate-General for Energy. 2000. *A Technical Study on Fuels Technology Related to the Auto-Oil II Programme - Final Report - Conventional Fuels*. Available: http://ec.europa.eu/energy/oil/fuels/ doc/conventional_fuels_en.pdf; and (ii) Pervin and Gertz. 2000. Cost of Compliance with EU standards.

[86] Personal Communication between John Courtis and fuel quality regulators in the PRC and Indonesia.

reforming capacity, and investments in catalytic reforming would be the first choice should there be a discussion to upgrade such refineries. As chapter 3 shows, although small topping refineries are numerous, they process a relatively small part of the crude that is refined in Asia. The rapid increase in refining capacity in Asia will further reduce this already low percentage. Small refineries in the United States initially preferred metallic additives and oxygenates. However, it is important to note that MMT now is used in less than 1% of the US gasoline supply (footnote 84), and in none of the gasoline supply in Australia, Brazil, India, and Japan, some of which had or still have a number of small refineries.

H. Conclusion

349. Emissions from vehicles depend on the combination of engine technology, including exhaust aftertreatment, and fuel specifications; thus, it is impossible to discuss one without the other. In this context, fuel specifications must include all the characteristics of the fuel and its additives. As vehicle emission standards have tightened over time, fuel specifications have had to be changed both to allow more advanced emission control technologies to be effectively implemented, and to mitigate increasingly evident health effects.

350. For many years lead was widely used as an octane enhancer in gasoline as it was readily available and provided the cheapest solution for the refiner. The cost of lead to society and especially to its children has proven to be immense over time. Most countries, including nearly all of those in Asia, have banned lead in gasoline because of its effects on human health, so that transport will no longer be a source of lead emissions. This effort has caused refineries to identify other means of covering the octane shortfall. In addition, many refineries must simultaneously reduce the amount of sulfur in fuel.

351. In addition to increasing capital investment, refiners can use selected crude oils or high octane blend-stocks, metallic based additives (other than lead), and oxygenates.

352. Less than 1% of the US gasoline supply uses metallic based additives. Very few metallic additives are used elsewhere in the world. Nevertheless, controversy over their use, especially of MMT and ferrocene, continues based upon potential health effects and effects on emission control systems. Some have expressed concern that the ban on leaded gasoline may result in new problems arising from the use of metallic additives such as MMT and ferrocene. For this reason, preliminary studies on the health effects of MMT are ongoing in the United States and Canada.

353. Vehicle manufacturers are responsible for maintaining low emissions for the lifetime of the vehicle through durable and effective operation of their modern emission control systems. They are seriously concerned that metallic ash-forming additives can degrade the operation of catalysts and other components, such as oxygen sensors, in an irreversible way that increases emissions. Thus, they recommend that high-quality gasoline should be used and that metallic ash-forming additives should be avoided.

354. Older vehicles and two- and three-wheelers that are not equipped with catalytic converters, oxygen sensors, and similar emission control systems are less affected by the use of metallic additives. Still, the risk of vehicle owners using fuel containing metallic additives in vehicles with modern emission control systems has led to a consistent recommendation by the automotive manufacturers that the use of ash-forming additives should be avoided altogether.

355. This chapter has highlighted the experience of refiners who, in the longer term, have chosen to meet the gasoline octane requirements through capital investment, blend-stock selection, and the use of certain oxygenates. Refiners initially used metallic additives more widely because of their financial appeal. MTBE was widely seen as an effective option for improving octane ratings. Concerns about contaminated water supplies bearing an unpalatable taste and odor have led the United States and Australia to ban MTBE. Refiners and vehicle manufacturers increasingly see ETBE as a preferred substitute for MTBE over ethanol because of the handling and RVP problems associated with the latter. The fact that in most countries, an overwhelming majority of fuel is now free of metallic based octane-enhancing additives is evidence of the cost-effectiveness of this route within the confines of existing regulations.

V. PRICING, TAXATION, AND INCENTIVES FOR CLEANER FUELS

A. Introduction

356. Fuel pricing and taxation policies have important implications for cleaner fuels in Asia. On the one hand, automotive fuel pricing and taxation regimes, whether more open or more regulated, can affect how the production of cleaner fuels is financed, the ease with which industry can secure financing, and the ability of industry to pass higher costs along to consumers. At the same time, where governments play strong roles or monopolize fuel supply, political will becomes important in financing cleaner fuels. Also, incentives such as differentiated fuel pricing are promising tools for accelerating cleaner fuel uptake. In Asia and around the world, tax differentials between fuels have been used to help establish markets for cleaner fuels and to support regulations. These cases offer lessons for developing similar policies for a new range of higher quality fuels in Asia.

B. Automotive Fuel Industry and Pricing Structure in Asia

1. Industry Structure in Asia

357. National oil markets vary according to the number of competitors and the degree of public ownership. On one end of the spectrum are national oil sectors characterized by unrestricted ownership and investment among a range of domestic and international private companies, while on the other end are sectors dominated by a single state-owned monopoly. Before the 1970s, major international oil companies, which had little difficulty raising capital from international financial markets, were the primary investors in global oil. The situation changed in the 1970s when producing countries asserted greater control over oil resources and began to establish national companies because of rising prices and concern over the security of supply. Subsequently, an increasing part of investments in the oil sector came from government budgets. Beginning in the 1980s, the global trend has been toward privatization and the introduction of competition amid falling oil prices and increasing government debt. A significant degree of market deregulation took place through the 1990s, and project financing has evolved into a mixture of ownership arrangements and joint ventures. In recent years, with high oil prices and the emergence of significant new demand in countries like the PRC and India, national oil companies have continued to play major roles in development and finance in the oil and energy sectors. As Table 5.1 notes, some of the largest oil companies in Asia still maintain a high degree of state ownership.

Table 5.1: Public Ownership in Asia's Major Oil Companies

Company	Country	Government Ownership (%)
PERTAMINA	Indonesia	100
Petronas	Malaysia	100
PetroChina	PRC	90
Indian Oil Corp.	India	82
Petroleum Authority of Thailand (International)	Thailand	68
Sinopec	PRC	55
Pakistan State Oil	Pakistan	52
Petron	Philippines	40

PRC = People's Republic of China, PERTAMINA = Perusahaan Tambang Minyak Nasional (National Oil Mining Company).
Source: Energy Intelligence Group. 2004. Rankings Based on Financial and Other Measures. *Petroleum Intelligence Weekly*. Available: http://www.energyintel.com/DocumentDetail.asp?document_id=137158; Indian Oil Corporation.

358. Most Asian countries have some domestic refining capability. Some countries are larger importers, most notably Hong Kong, China, and Viet Nam (despite being a large crude producer). Increasingly, Republic of Korea, Philippines, Taipei,China, and Singapore have become major regional exporters of refined products. Although India is a net importer, it has boosted domestic refining capacity in recent years.

359. While the majority of Asian countries are in the process of deregulating upstream and downstream oil sectors, the pace and approach of these reforms varies throughout the region. In terms of downstream and refining ownership, Asian countries can be categorized as public, private, or transitional (Table 5.2). Markets in Bangladesh and Indonesia continue to be dominated by state-owned monopolies. Although liberalization has been slow in Indonesia, liberalization of its downstream oil and gas sector has been discussed for several years. The 2001 Oil and Gas Law established the Oil and Gas Downstream Regulatory Body (BPH MIGAS) to regulate downstream activities, and National Oil Mining Company (PERTAMINA) became a limited liability company in 2003. Given the high international oil prices of recent years, the Government of Indonesia has deferred until 2010 plans for fully liberalizing the oil and gas sector and for abolishing fuel subsidies, contrary to the 2001 Oil and Gas Law which established a target of 2005 for the introduction of privatization.

360. Major national companies in India and Pakistan largely dominate the downstream sector. In India's case, major domestic, private conglomerates such as Reliance are playing greater roles in domestic refining. The PRC's state companies dominate refining and retailing, although import quotas and foreign ownership restrictions have eased as the country liberalizes in conformance with its accession to the World Trade Organization. Malaysia, Taipei,China, and Thailand have strong national oil companies, but significant private participation. In Taipei,China, the two major downstream companies, Chinese Petroleum Corporation and Formosa Petrochemical Corporation, are owned by the state, but significant competition exists among private actors in the retail sector. Japan, Republic of Korea, Singapore, and increasingly the Philippines are open markets dominated by private firms. In the Philippines, Petron (the state

controlled company), Shell, and Caltex dominate refining, although Caltex has replaced its refining capacity with an import terminal.[87]

Table 5.2: Ownership in Downstream Oil Markets in Asia

Country	Dominant Enterprises in Downstream/Refining	Ownership
Bangladesh	Bangladesh Petroleum Corporation	Public
PRC	CNPC, Sinopec, CNOOC BP, Exxon, Shell	Public/ transitional
India	Reliance, Hindustan, Indian Oil Corporation, Shell	Public/private
Indonesia	PERTAMINA, BP, Petronas	Public/ transitional
Japan	Nippon Mitsubishi Oil, Showa Shell, Tonen, Exxon	Private
Republic of Korea	SK Corp., LG-Caltex, Hyundai	Private
Pakistan	Pakistan State Oil, PARCO, OGDCL	Public/private
Philippines	Petron, Pilipinas Shell, Caltex	Public/private
Singapore	Shell, Exxon, SRC	Private
Sri Lanka	Ceylon Petroleum Corp.	Public
Taipei,China	Chinese Petroleum Corp., Formosa Petrochemical	Public/private
Thailand	PTT, Shell, Esso	Public/private
Viet Nam	–	–

BP = British Petroleum, CNOOC = China National Offshore Oil Corp., CNPC = China National Petroleum Corporation, Esso = sister company of Exxon Mobil, OGDCL = Oil and Gas Development Company Limited, PARCO = Pak Arab Refinery Ltd, PRC = People's Republic of China, PERTAMINA = Perusahaan Tambang Minyak Nasional (National Oil Mining Company), PTT = Petroleum Authority of Thailand (International), SRC = Singapore Refinery Company.
Source: United States Department of Energy, Energy Information Administration. 2005.

2. Automotive Fuel Pricing in Asia

361. Prices for petroleum products are determined typically by cost for crude, refinery production costs and margins, taxes, distribution costs, and profit margins. As the cost of crude and of refining differ marginally from country to country, the primary variants in national fuel prices are tax and pricing practices. Countries that are heavy importers of petroleum products tend to have higher tax rates than those that export petroleum products. However, a range of policy goals affect fuel taxation and pricing, including general revenue generation, road and infrastructure finance, price volatility control, redistribution of income, and reduction of environmental externalities. Health and environmental concerns typically are not consistently reflected in fuel taxation regimes in Asian countries.

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[87] Since oil market deregulation began in 1998, 62 new firms have entered the retail market. Their share of the market has increased from approximately 10% in 2000 to approximately 20% in mid-2004, which has placed significant downward pressure on retail fuel prices (the lowest of any non oil-exporting Asian country). The estimate of 20% is drawn from the US Department of Energy, EIA country brief for the Philippines.

362. Asian fuel tax practices can be grouped into four categories according to price range and tax policy: subsidized, low tax, medium tax, and high tax. Higher income and oil dependent economies generally have higher taxation regimes and as a result higher fuel prices. For example, diesel prices in Hong Kong, China, and Japan are generally among the highest in Asia while subsidized diesel prices in Indonesia and Malaysia are among the lowest. Tax policies are closely related to pricing regimes, which are determined primarily by either the market or the state. Market pricing is the norm in industrialized countries, where demand is typically high and stable, and where there are private refineries in sufficient numbers to sustain a competitive market. In markets dominated by the state, prices are set according to government controls and price formulas. Price controls are often associated with some form of subsidy, in which governments absorb the difference between consumer prices and world prices.

Table 5.3: Automotive Fuel Pricing and Taxation Practices in Asia

Country	Pricing	Taxation Subsidy Practice[a]	Fuel tax as % of total tax revenue (2005)
Bangladesh	Controlled/transitional	low taxation/subsidy	1
Cambodia	Controlled	medium taxation	
Hong Kong, China	Market	high taxation	
India	Transitional	medium taxation	8
Indonesia	Controlled	subsidies	(6)
Japan	Market	high taxation	11
Malaysia	Controlled	subsidies	(2)
Pakistan	Transitional	low taxation/subsidy	4
Philippines	Market	low taxation/subsidy	0
PRC	Controlled/transitional	low taxation/subsidy	4
Singapore	Market	medium taxation	3
Sri Lanka	Transitional	low taxation/subsidy	7
Republic of Korea	Market	high taxation	19
Taipei,China	Transitional	medium taxation	
Thailand	Transitional	low taxation/subsidy	2
Viet Nam	Controlled/transitional	low taxation/subsidy	

PRC = People's Republic of China.

[a] Approaches based on 2005 information. At that point in time, Brent crude oil cost approximately US$42 per barrel.

Source: Metschies, Gerhard. 2007. *International Fuel Prices 2007, 5th Edition*. Available: http://www.gtz.de/de/dokumente/en-international-fuelprices-final2007.pdf

363. Pricing mechanisms for petroleum products in Asia range from market pricing to controlled pricing with transitional variations (Table 5.3). Japan, Republic of Korea, Singapore, and increasingly the Philippines rely on market pricing; Bangladesh, Indonesia, Malaysia, and Viet Nam have direct price controls. These latter countries typically set prices at the local cost of production plus a fixed percentage for different market segments and taxes. The production cost

is often set by the government, although it may attempt to index this cost to an import parity price. A typical price formula, such as the one applied in Bangladesh, would consist of an import parity price, plus storage cost, domestic distribution, wholesale profit margin, retail margin, value added taxes, and other taxes. The government may also employ a price band that allows producers to set prices within a certain range (e.g., plus or minus 10% in Viet Nam). Although Indonesia has historically fully administered fuel prices, it has in recent years begun to open pricing to world fluctuations. In 2002, the Government of Indonesia announced a new formula allowing PERTAMINA to modify fuel prices every month based on the Mid Oil Platt Singapore prices. Shortly thereafter, however, it set a price band in order to protect against extreme fluctuations in world prices. The price index was set at Mid Oil Platt Singapore plus 5% in December 2002. By January 2003, the Government had suspended the index practice due to high world oil prices, and it has since let prices rise significantly in recent years.[88]

364. PRC, India, Pakistan, Sri Lanka, Taipei,China, and Thailand might be described as "transitional" in terms of their degree of price liberalization. These governments have typically implemented measures to move toward market pricing and in particular have opened pricing to international price fluctuations, but they tend to maintain certain controls like frequent excise tax adjustments or the continued use of pricing formulas based on import parity-pricing. Pakistan has maintained for many years a policy of “pan-territorial” energy pricing or uniform pricing across the country. The origins of this policy lie in the political goal of promoting national unity in Pakistan. Ex-refinery prices are set bi-monthly by the Ministry of Petroleum and based on import parity prices or the "free on board" prices of equivalent products. Import parity prices are averaged for the fortnight as quoted in the Arab Gulf Region, to which are added elements like bank charges, customs duties, and so forth.

365. Although India officially dismantled its Administered Pricing Mechanism, it still intervenes to keep prices from rising. The administered pricing system was originally set up in the late 1970s, as so-called "retention pricing", where refineries and distributors were compensated on the basis of a cost-plus formula (i.e., operating costs plus a 12% return), and prices were fixed accordingly. In 1997, the Government introduced "import parity" pricing on gasoline and diesel, but the Ministry of Petroleum and Natural Gas still screens prices for diesel and gasoline on a fortnightly basis. In August 2004, the Government developed a price band in which retailers were able to pass higher costs of production onto consumers, but the cap has not been high enough to keep up with rising costs for international crude.[89]

366. Thailand relies mainly on market prices for production cost prices and has a transparent tax regime. It does, however, intervene at times in final pricing, often with funds from its oil fund tax. Beginning in 1998, the PRC has set prices on the basis of international price fluctuations. Sri Lanka sets prices monthly on the basis of an import-parity formula introduced in 2002.

3. Fuel Subsidies in Asia

367. The International Energy Agency (IEA) defines an energy subsidy as any government action that concerns primarily the energy sector that lowers the cost of energy production, raises the price received by energy producers, or lowers the price paid by energy consumers. Although energy subsidies are common throughout the world, it is difficult to measure them. In addition,

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[88] US Embassy Jakarta. 2004. *Petroleum Report Indonesia 2002-2003*. Available: http://www.usembassyjakarta.org/econo/petro2003-toc.html

[89] TERI. 2005. *Petroleum Pricing in India: Balancing Efficiency and Equity*. New Delhi: The Energy and Resources Institute, India

many subsidies often reflect entrenched industry practice and may not be viewed locally as subsidies. Automotive fuel consumption in some Asian countries has been subsidized to keep prices lower for consumers. Many Asian governments have tended to subsidize diesel fuel to support commercial transport and economic growth, as reflected in lower diesel prices compared to those for gasoline. Some Asian countries, including Indonesia and Malaysia in 2004, also subsidize domestic prices compared to international prices. Fuel subsidies in Malaysia cost the Government US$1.3 billion in 2004.[90] In addition to direct subsidies on prices and production costs, there may also be indirect subsidies such as preferential rates for shipping for government enterprises. Subsidies to protect consumers from international prices shocks have been more common in recent years. Other forms of subsidies common in Asian fuel markets include preferential pricing and tax treatment for unleaded gasoline and alternative fuels like natural gas to support public health and energy conservation and diversification programs.

4. Impact of Rising International Oil Prices in Asia

368. The higher international oil prices of recent years have had a significant impact on Asian fuel markets and pricing practices. Most notably, high international prices have forced countries that have typically subsidized domestic fuel consumption to reduce controls to ease the strain on government budgets. Several countries initially attempted to absorb the international fluctuations by increasing subsidies. In early 2004, to mitigate rising prices, Thailand introduced a subsidy on diesel that by June 2005 had reportedly cost the Government B88.37 billion (US$2.2 billion).[91] In 2004, Indonesia spent four times the Rp14 trillion (US$1.5 billion) that it had planned to spend on fuel subsidies.[92] To keep oil prices low, Malaysia forewent a fuel sales tax in 2005, which amounted to RM7.9 billion (US$2.2 billion).[93]

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[90] ADB. 2005. *The Challenge of Higher Oil Prices – Asian Development Outlook 2005 Update*. Manila. Available: http://www.adb.org/Documents/Books/ADO/2005/update/part030000.asp

[91] Energy Intelligence Group. 2005a. Thailand Approves Subsidy Bond. *International Oil Daily*. Available: http://www.energyintel.com/DocumentDetail.asp?Try=Yes&document_id=149319&publication_id=31

[92] *The Economist*. 2004. Pump Priming. 30 September.

[93] Tan, Deyi, and Daniel Lian. 2005. Malaysia: The Ugly Face of Fuel Subsidies. *Morgan Stanley - Global Economic Forum*. Available: http://www.morganstanley.com/views/gef/archive/2005/20050825-Thu.html

Table 5.4: Super Gasoline Prices in Asia, 1995–2006
(US$/liter)

Country	1995	1998	2000	2002	2004	2006
India	0.48	0.56	0.60	0.66	0.87	1.01
Indonesia	0.44	0.16	0.17	0.27	0.27	0.57
Japan	1.25	1.02	1.06	0.91	1.26	1.09
Republic of Korea	0.79	0.93	0.92	1.09	1.35	1.65
PRC	0.27	0.28	0.40	0.42	0.48	0.69
Taipei,China	0.59	0.57	0.61	0.51	0.71	0.83
Thailand	0.34	0.30	0.39	0.36	0.54	0.70

PRC = People's Republic of China, US$/liter = United States dollar per liter.
Source: Metschies, Gerhard. 2007. *International Fuel Prices 2007, 5th Edition*. Available: http://www.gtz.de/de/dokumente/en-international-fuelprices-final2007.pdf.

Table 5.5: Commercial Diesel Prices in Asia, 1995–2006
(US$/liter)

Country	1995	1998	2000	2002	2004	2006
India	0.19	0.21	0.39	0.41	0.62	(0.75)
Indonesia	0.20	0.07	0.06	0.19	0.18	0.44
Japan	0.75	0.69	0.76	0.66	0.95	0.90
Republic of Korea	0.33	0.41	0.66	0.64	0.95	1.33
Taipei,China	0.38	0.41	0.50	0.41	0.55	0.71
PRC	0.24	0.25	0.45	0.37	0.43	0.61
Thailand	0.30	0.27	0.35	0.32	0.37	0.65

PRC = People's Republic of China, US$/liter = United States dollar per liter.
Source: Metschies, Gerhard. 2007. *International Fuel Prices 2007, 5th Edition*. Available: http://www.gtz.de/de/dokumente/en-international-fuelprices-final2007.pdf.

369. Persistent price rises have led to difficulties for Asian countries. Indonesia's policy of subsidizing domestic fuel prices significantly strained Government finances, with subsidies at one point accounting for about 7% of gross domestic product. In April 2005, the Government disbursed only Rp4.1 trillion (US$2.5 billion), rather than the planned Rp24 trillion in subsidies leading to a financial crisis for PERTAMINA and supply shortages across the country. Subsequently, the Indonesian Government raised pump prices by an average of 126%, which was the second hike of 2005 after a relatively modest 29% increase in March. Gasoline prices rose 87%, and diesel fuel 104%, while the price of kerosene almost tripled. In raising the prices, the Government aimed to halve its anticipated spending level on subsidies to Rp3.98 trillion (US$4.3 billion) in 2005. Fuel subsidies will now be phased out through a series of fuel price

increases over the next 5 years. The Government has provided direct cash subsidies to low income groups to ease the burden of price increases.[94]

370. Thailand managed to hold the price for diesel at US$0.36 per liter between January 2004 and February 2005, but by summer 2005 it had ended the subsidy, costing the country an estimated US$2.2 billion.[95] Thailand also ended gasoline subsidies in 2005 and raised diesel prices by US$0.073 per liter. During this period, Malaysia also began to raise fuel prices. Between October 2004 and March 2006, regulated pump prices rose 40% for gasoline and 100% for diesel.[96] Lastly, Bangladesh's Government has also let prices rise by about 15% in recent years.

371. PRC and India, which have allowed the brunt of price increases to be carried by state-owned oil refiners, have also begun to allow domestic prices to rise. They have subsidized refiners in light of persistent low margins and losses resulting from capped domestic prices and high international crude prices. In India, the Ministry of Petroleum and Natural Gas allowed price increases in June and September 2005. Also for fiscal year 2005, the Government assumed a portion (about US$2.5 billion) of the refinery losses, for which bonds were to be issued to oil companies (footnote 90). In 2005, the PRC gave Sinopec a windfall payment of US$1.18 billion to compensate for its refining losses and subsequently introduced a "special revenue charge" on crude oil producers in order to subsidize refiners. The tax, which applies to all oil producers in the PRC, varies according to international crude prices between 20% and 40% on amounts exceeding US$40 per barrel.

372. Increased fuel prices in recent years have also led to lower demand in Asia with impacts for economies and lower income groups in particular. In the first 5 months of 2005, oil demand fell by 8% in the Philippines (footnote 94). Many Asian countries are particularly vulnerable to price spikes due to the lower proportional tax rates on fuel. Because most countries place a fixed tax per liter on automotive fuels, high tax regimes tend to be more sheltered from price increases. This explains why high international prices have had a greater impact on domestic prices in low tax regime countries in Asia than in those countries with higher tax regimes such as the Republic of Korea, or in most European countries.

5. Implications for Cleaner Fuels in Asia

373. Ownership structure and tax and pricing regimes for petroleum fuels affect how cleaner fuels will be introduced in Asia. Over the long term, open markets appear to be more conducive to the penetration of cleaner fuels than heavily regulated and closed markets. Competition among firms in open markets helps to encourage investments in new products and fuels, even as government policy remains the primary driving force. By comparison a closed market, with a state energy supplier, will typically not facilitate the production of cleaner fuels unless the government mandates it.

374. Market ownership and pricing policy affect opportunities for raising capital investments for cleaner fuels. Highly regulated markets in low income countries are likely to have difficulty

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[94] *Energy Economist*. 2005. Philippines Gets Efficient. September.

[95] Shrestha, Ram M., S. Kumar, S. Martin, and N. Limjeerajarus. 2006. *Report on Role of Renewable Energy for Productive Uses in Rural Thailand*. Pathumthani, Thailand: Global Network on Energy for Sustainable Development. Available: http://www.gnesd.org/Downloadables/RETs/AIT%20RETs%20final%20draft.pdf

[96] *Reuters*. 2006. Malaysian Police Quash Protests. Available: http://english.aljazeera.net/NR/exeres/D4ECE099-0295-47F5-9F30-B41262C464D9.htm

raising capital for refinery upgrades if public resources are limited and there are restrictions on foreign ownership and investment. This has been a major problem, for example, for Indonesia in financing unleaded gasoline, where proposed solutions that would allow PERTAMINA, the state-owned oil company, to produce unleaded gasoline have been slow to materialize because of a restriction on foreign ownership of refineries, price controls, and limited public financing options.

375. In addition, industry is generally unwilling to invest in refinery upgrades when there is an inadequate guarantee that it can recover costs through price increases. Perceived inadequacies in potential demand, inflexible or unpredictable price controls, and price caps can discourage Asian market actors, including potential importers and firms with state ownership, from investing in cleaner fuels. A number of Indian firms, for example, have recently declined to invest in refinery upgrades for lower sulfur diesel because Government price controls preclude higher retail prices. At the same time, some Indian oil refiners are investing in upgrades to meet demand in foreign markets, where cleaner fuels demand higher prices, while turning to imports to meet tighter domestic fuel standards. The Indian Oil Corporation imported 11 billion barrels in transport fuels during fiscal years 2004 and 2005, including 1.7 million barrels to meet higher fuel specifications, from Republic of Korea, Singapore, and Taipei,China. In the same year, refiners in India operated at nearly 100% capacity, producing 2.4 million barrels per day of petroleum products. Of this, state companies exported almost 176,000 barrels per day, and Reliance exported 205,000 barrels per day, equivalent to nearly one-third of the capacity at its Jamnagar refinery.[97]

376. While the market can and does provide cleaner fuels in countries that allow imports and flexible fuel pricing, suggesting that open markets are good for cleaner fuels in general, experience also shows that cleaner fuels can be bought or produced if the political will is sufficient, regardless of the market orientation of the downstream sector. In the 1990s, Bangladesh, Pakistan, Philippines, and Viet Nam through regulation rapidly introduced unleaded gasoline despite having a relatively closed downstream market, thus demonstrating the importance of political will in introducing cleaner fuels in different economies throughout the region. Viet Nam has recently taken a similar approach to the introduction of lower sulfur fuels, despite the higher costs imposed on importers.

377. Furthermore, although arguably not as efficient as open markets, state-controlled markets with controls on pricing may be more expedient agents in producing cleaner fuels when the political will exists to mandate cleaner fuels. State-controlled refining firms with large parent companies, operating with subsidies and soft budgets may, in fact, have ready access to financing where the political will exist to support investments in cleaner fuels exist (similarly, oil producers in the PRC have been recently taxed to subsidize local refiners) or where controlled prices would otherwise render such investments unattractive. Also, administered pricing may provide greater leverage to governments in pricing cleaner fuels more inexpensively than other fuels.

C. Asian and International Incentives for Cleaner Fuels and Vehicles

378. Introducing higher quality fuels and especially reducing specific properties in fuels such as sulfur depend on a range of regulatory actions, including fuel specifications and bans, pricing

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[97] Energy Intelligence Group. 2005b. *Petroleum Intelligence Weekly*. May. Available: http://www.energyintel.com/PublicationHomePage.asp?publication_id=4

and taxation policies, incentives, and public procurement and education. To improve fuel quality, governments typically issue a regulation or product specification. To accelerate investments, support regulations, and encourage the market for cleaner fuels, governments can and often do intervene with some form of incentive in addition to regulations. Possible approaches include differentiated consumption and production taxes on fuels, subsidies or other incentives for refiners, and similar measures for cleaner vehicles that can indirectly support the market for cleaner fuels and vehicles.

379. A common approach among governments around the world has been to differentiate taxes on automotive fuel sales, creating a relative advantage for a particular higher quality fuel. This tax difference is often passed on to consumers in differentiated pump prices. This policy is an example of a market-based or economic instrument, which has been used mainly in OECD countries in recent decades to support environmental policies. When environmental policies began to be adopted in the 1960s and 1970s, authorities relied primarily on the regulatory approach, prescribing objectives, standards, and technologies such as ambient standards, emission standards, production process standards, and product standards, based on best available technology. Academic economists developed economic approaches that entered into mainstream policy discourse in the 1980s. Economic instruments such as green taxes purported to offer a more cost-effective and flexible means of environmental control that gave greater decision making power to competitive markets and incorporated environmental policy into market rules and economic development goals. Such instruments were intended to be less costly for society overall; to give long term incentives for innovation; to act as a source of tax revenue (that could be used for other social projects or to correct the distributional impacts of the environmental taxes); and to provide learning experience in the pricing of environmental services in general. Most important, it was argued that economic instruments did not require that regulators have comprehensive and accurate knowledge of workings and capacities of industry, as is the case with regulations.

380. Experiences with economic instruments have been more or less productive. With regard to the vehicle and fuels sectors, the experience has been that the command and control approach has been generally effective at pushing the development of advanced technologies, and that economic instruments were effective at accelerating their introduction. In some cases, the information requirements for setting tax or incentive rates and prices have been higher than anticipated. More recently, a portfolio approach that includes a role for regulations, economic instruments, and other techniques for specific problems is being viewed as more appropriate than taking an either/or approach to command and control and market-based policies. This also applies to fuel quality improvements. Tax policies and incentives help to lower the overall cost to society of meeting regulations by encouraging those companies with the greatest capacities to take the lead, but these tax policies are nonetheless complemented by regulations, public outreach, and other tools. As the following examples and Table 5.6 show, a number of Asian countries have made some use of cleaner fuel or vehicle tax incentives.

1. Differentiated Fuel Pricing and Taxation

381. Differentiating tax rates (or prices) between fuels, through adjustments in the excise, import duty, or other tax, is a powerful instrument for supporting cleaner fuels—it helps to level the playing field for more expensive cleaner products. Differentiated pricing at the pump also sends a clear signal to motorists concerning the relative social costs of different fuels. One common concern with adjusting taxes is lost public revenue. However, tax rates can be modified to capture changing fuel demand. Tax incentives have been applied most extensively in the global phase-out of leaded gasoline. The European experience in the early 1990s shows that

the price differential between leaded and unleaded petrol was directly and positively related to the market penetration of unleaded gasoline. Tax differentials have also been used in helping to introduce unleaded gasoline in Asian countries, although not in all instances (Table 5.6). There has also been longstanding pricing support for alternative fuels like LPG in Japan and the Republic of Korea or CNG in India.

382. While differentiated fuel taxes are the most common market-based approach to accelerate cleaner fuels, direct subsidies to producers for refinery upgrading can also be used. In 1990–1992 for example, Japan instituted a direct tax incentive to subsidize refinery investments required to lower sulfur content in diesel fuel below 2,000 ppm. Firms could opt for a 7% deduction in corporate tax or 30% accelerated depreciation on the purchased equipment. In 2004, the Government of Japan provided a direct incentive for refiners to produce 10 ppm sulfur diesel earlier than the January 2007 regulation. At the time the Government acknowledged that raising prices to cover the costs of lower sulfur diesel would be difficult for industry due to the deflated Japanese economy and heavy competition in Japan. The Government subsidized a total of US$90 million over 3 years (2004–2006) accounting for about 2–4% of the actual investment of the petroleum industry in Japan. The subsidy was allocated on a first come first serve basis for those companies that produced or imported the fuel. The scheme was developed by the Ministry of Industry, the Ministry of Finance and the Ministry of Environment and was funded from the Oil and Energy Conservation Fund, a duty dedicated to oil conservation and stockpiling, which typically generates around ¥500 billion annually.

Table 5.6: Fuel Price and Tax Differentials in Asia

Country	Fuel Incentive
Bangladesh	2006: CNG at Tk8.5/liter (US$0.13)[a] compared to Tk42/liter (US$0.64) for gasoline. Price for CNG lower since 1998 100% tax exemption on import of CNG conversion kits and dispensing units
PRC	2005: Retail prices on gasoline and diesel in Beijing were raised by a greater margin than in other cities to compensate refining companies for the increased cost of providing Euro 3 in capital 2005: The fuel excise tax is CNY0.28/liter (US$0.03) for leaded petrol, CNY0.20/liter (US$0.02)[b] for unleaded 1999: Leaded gasoline tax increased to make its price no lower than unleaded gasoline
Hong Kong, China	2000: 50 ppm diesel HK$0.89/liter (US$0.11)[c] less than conventional 500 ppm 1991: Unleaded gasoline average HK$0.52/liter (US$0.07)[d] less tax than leaded gasoline over 8 years
India	2005: CNG exempted from VAT tax
Japan	2004: Total tax on non-commercial LPG ¥12.9/liter (US$0.13) versus total tax on unleaded gasoline at ¥59.2/liter ($0.57)[e]
Republic of Korea	2004: W277/liter (US$0.27) less on ULSD relative to conventional diesel
Malaysia	2003: RM0.585/liter (US$0.15) for CNG compared to RM1.35/liter (US$0.36) for gasoline (RON 97) and RM0.761/liter (US$0.2) for diesel[f] 1991: Unleaded gasoline retail price 2.65% lower than leaded gasoline
Nepal	LPG incentive
Philippines	1999: Unleaded gasoline P1.0 (US$0.25)[g] less than leaded 2003: Lower duty rate on natural gas vehicle engines/CNG price lower than diesel
Singapore	1991: Leaded gasoline raised S$0.12/liter (US$0.07)[h] over unleaded gasoline
Thailand	Planned: Biodiesel (5%) at least B0.75/liter (US$0.02) less than diesel 2006: Unleaded gasoline (95) = B27.14/liter (US$0.72); diesel = B25.49/liter (US$0.68); CNG = B8.5/liter (US$0.23); LPG = B16.81/liter (US$0.45) 2005: Gasohol (90% petrol/10% ethanol) B0.50/liter (US$0.01) cheaper than octane-95 petrol 1991: Unleaded gasoline B1.00/liter (US$0.04)[i] less excise tax than leaded gasoline

B = baht, CNG = compressed natural gas, CNY = yuan, HK$ = Hong Kong dollar, LPG = liquefied petroleum gas, P = peso, ppm = *please define**, PRC = People's Republic of China, RM = ringgit, Malaysia, RON = research octane number, S$ = Singapore dollar, ULSD = ultra low sulfur diesel, US$ = United States dollar, VAT = value added tax, W = won, ¥ = yen.

[a] Converted May 15, 2006 rate
[b] Converted Dec 31, 2005 rate
[c] Converted Dec 31, 2000 rate
[d] Converted Dec 31, 1998 rate
[e] Converted Dec. 31, 2004 rate
[f] Converted Dec 31, 2003 rate
[g] Converted Dec 31, 1999 rate
[h] Converted Dec 31, 1991 rate
[i] Converted Dec 31, 1993 rate

Source: Authors

a. Hong Kong, China: Unleaded Gasoline

383. The Hong Kong, China Government in 1991 instituted a tax differential to stimulate the market for unleaded gasoline that averaged HK$0.52 over an 8-year phase out period. The market changed to unleaded gradually, and leaded was banned in 1999 when the market share of unleaded exceeded 90%. Table 5.7 indicates the progressive market penetration of unleaded petrol in Hong Kong, China in accordance with a steady price and tax differential throughout the 1990s. The slow rise has been attributed to the relatively small price advantage that the policy created for unleaded.

Table 5.7: Sales, Prices, and Duties for Gasoline in Hong Kong, China, 1991–2001

	Local Sales (kiloliter)		Listed Price (HK$/liter)		Duties (HK$/liter)	
Year	**Leaded**	**Unleaded**	**Leaded**	**Unleaded**	**Leaded**	**Unleaded**
1991	383,026		7.87	7.07	4.17	3.72
1992	173,359	240,515	7.70	7.41	4.59	4.09
1993	160,853	291,019	8.10	7.76	5.03	4.48
1994	136,564	338,863	8.80	8.41	5.46	4.86
1995	113,380	353,792	9.44	9.00	5.90	5.25
1996	92,337	376,791	10.20	9.7	6.43	5.72
1997	73,508	408,010	10.79	10.24	6.82	6.06
1998	45,721	449,091	10.69	9.84	6.82	6.06
1999	3,990	507,502		10.34		6.06
2000		553.298		10.70		6.06
2001		575,950		10.40		6.06

HK$ = Hong Kong dollar.
Source: Hung, Wing-Tat. 2003. Taxation on Vehicle Fuels: Its Impacts on Switching to Cleaner Fuels. *Energy Policy* 34(16): 2566-71. Available: http://dx.doi.org/10.1016/j.enpol.2004.08.018

b. Thailand: Unleaded Gasoline

384. Thailand introduced unleaded gasoline in 1991 as part of a larger air pollution control strategy. The initiative was led by the National Energy Planning Office (an office of the prime minister) and included multiple ministries, as well as oil and auto companies. The initiative required reformulation in order to maintain necessary octane levels and performance. For the short term, it was possible to import low-lead and unleaded gasoline; however, major modifications of local refineries were necessary to produce reformulated unleaded gasoline for the longer term.

385. Although the costs of producing unleaded gasoline were higher than producing leaded gasoline (the net additional cost was estimated to be B0.5 per liter), the Government made the price for unleaded B0.3 per liter less than leaded. To achieve this price, the Government collected B1 per liter less in excise tax on unleaded gasoline, as Table 5.8 shows, for locally produced and imported products. This cost was financed primarily from the Government's oil fund, which had a B6.65 billion surplus in 1991 due to low world oil prices and a simultaneous

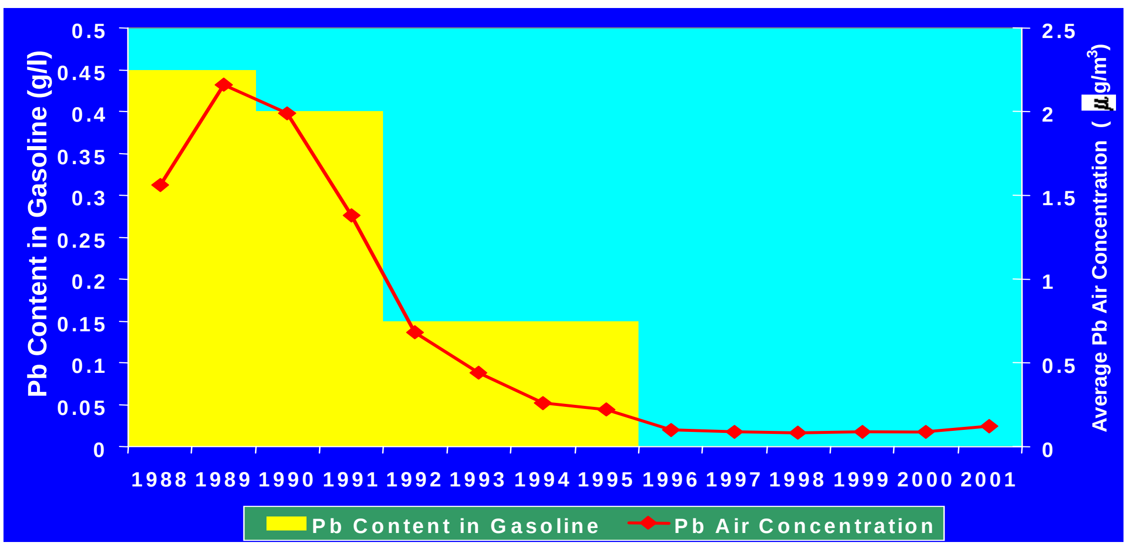
tax increase of B0.4 per liter on diesel fuel. In addition, the import duty on MTBE was lowered from 30% to 1% to encourage MTBE as a substitute for lead additives.

Table 5.8: Excise Tax on Gasoline in Thailand, 1991–1992
(baht/liter)

Product	March 1991	May 1991	June 1991	Sept 1991	Jan 1992
Unleaded	–	2.9290	2.9290	3.1900	2.5850
Regular	3.9390	3.9390	3.9390	4.2900	3.3550

Source: Sayeg, Phil. 1998. *Successful Conversion to Unleaded Gasoline in Thailand. World Bank Technical Paper 410*. Washington, DC: World Bank.

Figure 5.1: Lead Content in Gasoline and Lead Air Concentration in Bangkok, 1988–2001
(g/l gasoline and µg/m^3 air)



g/l = grams per liter, µg/m^3 = microgram per cubic meter.
Source: Wangwongwatana, Supat. 2002. Air Quality Management in Bangkok: Trends and Challenges. Presented at the Better Air Quality in Asian and Pacific Rim Cities 2002 Workshop (BAQ 2002), Hong Kong, 16 December. Available: http://www.cse.polyu.edu.hk/~activi/BAQ2002/BAQ2002_files/Proceedings/Subworkshop1/sw1a-5Wangwongwatana_Final.pdf.

386. Unleaded gasoline entered the Thai market slowly and steadily. Only in 1995, a year prior to the ban on leaded gasoline did unleaded gasoline penetrate 100% of the market. According to the National Energy Policy Office, a lack of consumer awareness significantly inhibited the quicker uptake of premium unleaded fuel. Many drivers perceived unleaded fuel as a lower grade and questioned its safety. In response, the Government launched an educational campaign for motorists.

c. Philippines: Unleaded Gasoline

387. In 1999 unleaded gasoline in the Philippines was assessed Php1.00 less excise tax than leaded (Php5.35 to Php4.35) through a policy initiative of the Department of Energy and the Department of Environment and Natural Resources. The result was approximately a Php0.5 pump price advantage for unleaded, which in the initial year of operation expanded its market share from 20% to 34% in Metro Manila and 7% to 15% in the rest of the country. Taxes for less price sensitive fuel products were increased in an attempt to recover lost tax revenue on unleaded gasoline.

388. When unleaded gasoline was mandated in 1999, the supply was met first through increased imports, and then gradually by local producers. Although the price differential helped to generate consumer adoption of the fuel, it was not considered an important factor in encouraging local refineries to invest in unleaded fuels. Investments that did follow were more likely a response to ADB loans to the Government, which were conditional on the development of an effective ban on unleaded gasoline in Metro Manila.

d. Sweden: Low and Ultra Low Sulfur Diesel

389. Sweden introduced 10 ppm and 50 ppm sulfur diesel to the Swedish market in 1991 with the assistance of a tax differential. In that year, the tax on 10 ppm diesel was lowered by 20 European currency units (ECU) per cubic meter, and by a further 12 ECU a year later. Also in 1991, the tax on 50 ppm diesel was increased by 4 ECU and then decreased the next year by 8 ECU. The tax on 350 ppm was increased by 21 ECU in 1991 and kept at that level in 1992. Shortly thereafter, 10 ppm diesel accounted for 85% of the market share, which was estimated to reduce particulate emissions by 10%–30%, $S0_2$ emissions by 99%, and NO_X by 11%–15%.[98]

390. The tax differentials in Sweden were significant enough to motivate industry to invest in advance of regulations without increasing prices to consumers. Increased prices per liter for the refiner on higher quality fuel sales helped to cover the extra cost of investment. The total value of tax reductions (on higher quality fuels) equaled 600 million ECU, and the total value of tax increases (on lower quality fuels) equaled 500 million ECU between 1991 and 1996, suggesting a revenue loss of 100 million ECU from 1991 to 1996. Eighteen and one-half billion ECU in tax revenue were collected from transport fuels in that period, and industry invested approximately 540 million ECU in response to the tax differentials (footnote 98).

e. United Kingdom: Low Sulfur Diesel

391. The United Kingdom (UK) introduced 50 ppm diesel in 1997, when the average sulfur content was 200 ppm. A preferential tax rate of £.01 per liter for low sulfur diesel (LSD) over conventional diesel was implemented that year to offset additional production costs and to encourage diesel retailers to convert the diesel sold at their pumps. To accelerate the conversion, the differential was increased to £.02 in 1998, and to £.03 the following year. The UK had nine major and three smaller domestic refining units. In 1997, Shell, Total, ELF, Futura, and Green Energy began supplying LSD. However, motorists had generally limited access to the cleaner fuel, and producers continued to manufacture conventional diesel. More companies were producing the fuel in 1998, and by 1999, with the £.03 per liter advantage, all companies

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[98] Arthur D. Little. 1998. *Case Study: The Introduction of Improved Transport Fuel Qualities in Finland and Sweden. A Report to the Governments of Finland, Norway and Sweden*. Arthur D. Little

were supplying the higher quality fuel. By August 1999, LSD had achieved 100% share of the market, six years ahead of the EU mandate.

392. The UK tax differential was introduced by the Department of Environment, Transport and the Regions, but the final decision was taken by the Treasury. The tax differential resulted in some revenue loss for the Government. In 1997, when the £.01 differential was introduced, the cost in tax revenue was calculated at £15 million per year. By 1999, with the increase to £.03 per liter and the market shift to the lower-taxed LSD, the revenue cost was estimated at 400 million pounds per year.

393. These measures were taken as part of a larger fuel quality strategy in the UK, which beginning in 1993 consisted of a fuel duty escalator and several differentials to help mitigate local air pollution and reduce greenhouse gas emissions. Although the UK did not have a tradition of using a fuel tax for environmental purposes, its commitments under the National Air Quality Strategy and the Kyoto Protocol provided the impetus for these policies. Moreover, the public awareness was high about the benefits of LSD, with a number of supporting civil movements. Bus companies also publicized their use of LSD as a form of marketing and public relations.[99]

f. Hong Kong, China: Low Sulfur Diesel

394. Hong Kong, China, introduced a tax advantage for LSD in July 2000 along with tighter vehicle standards and other air improvement measures. The tax differential was HK$0.89 for 50 ppm diesel compared to the conventional 500 ppm. LSD eventually penetrated 100% of the market during the summer of 2000, at which point the pump prices for LSD and regular diesel were equal. The Government was further able to mandate higher, Euro 3, vehicle standards, and to undertake an extensive diesel oxidation converters retrofit program. The measure was seen as instrumental in achieving rapid market penetration for the cleaner diesel prior to the regulation in 2002.

395. A number of groups were involved in developing Hong Kong, China's policy, including the Environment Bureau, the Environment Protection Department, and oil and vehicle companies. Prior to introducing the tax instrument, internal studies were prepared on the costs and benefits of the differential. As the tax department was not readily willing to forgo revenue, the decision on the policy had to come from the top of Government. It should be noted that following an economic downturn, local truck unions waged a successful lobby to retain the tax advantage, and the Government has been unable to reinstate the original tax rate on diesel.

396. There were no major public outreach efforts, as there were for the introduction of unleaded gasoline in 1991 because public support for the higher quality fuel was anticipated and there were no anticipated adverse impacts on vehicle operation. Along with other programs, the measures helped to reduce the number of smoky vehicles by more than 80% from 2000 to 2004. At the same time, a subsidy was implemented for retrofits of light and heavy duty diesel vehicles, including for diesel oxidation catalysts and particulate traps.

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[99] HM Customs and Excise. 2000. *Using the Tax System to Encourage Cleaner Fuels: The Experience of Ultra-Low Sulphur Diesel*. Norwich. Available: http://www.hm-treasury.gov.uk/media/B/E/89.pdf

2. Differentiated Vehicle Pricing and Taxation

397. An important component of a government's overall strategy to reduce vehicle emissions are tax incentives for tighter standards and lower emission vehicles that often rely on higher quality or cleaner fuels (Table 5.9). In terms of cleaner fuels, tax incentives for tighter standard vehicles are an indirect signal to oil producers that higher quality fuels will be required for new fleets, as in Singapore, where oil producers have supplied Euro 4 fuels to incentivized market segments like diesel taxis, before implementation of country-wide Euro 4 emission standards.

398. Vehicle incentives generally include fee exemptions and tax credits for cleaner or more efficient vehicles. Vehicle taxes for consumers are often assessed as acquisition, registration, or road taxes, and can be differentiated between products in the same fashion as fuel products. As with fuel tax incentives, vehicle tax incentives will often be used in conjunction with regulations to accelerate market uptake.

399. Market-based approaches targeting manufacturers, such as the use of emission standard quotas and targets, are aimed at innovation rather than the accelerated implementation of established standards.

Table 5.9: Vehicle Price and Tax Differentials in Asia

Country	**Vehicle Incentive**
PRC	2006: Cars with engines exceeding two liters face consumption tax of 20%, up from 8%, while taxes on smaller cars will remain unchanged or will be reduced 2005: 30% consumption tax exemption on vehicles with installed OBD 2005: CNY4,000 (US$495.00) subsidy for scrapped or dismantled buses and trucks used for eight to 10 years 2003: 30% consumption tax exemption for automakers meeting Euro 3; 30% excise tax reduction on Euro 2 light duty vehicles in Beijing
Japan	2004: Hybrid electric vehicles charged 0.8% of retail prices for registration tax and diesel/petrol vehicles are charged 3% 2004: 11-year-old diesel vehicles and 13-year-old gasoline vehicles pay 10% additional tax 2001: 25%–75% tax reduction for gasoline and diesel vehicles meeting higher NO_X emission standards
Republic of Korea	2004:CNG buses exempted from VAT and acquisition taxes, equivalent to approximately US$3,000 per bus
Malaysia	2003: 50% reduction in road tax for CNG vehicle
Nepal	Tax incentive of up to 33% for electric vehicles
Singapore	2006: Euro 4 taxis get 40% rebate on Additional Registration Fee and Euro 4 buses and commercial vehicles 5%; Euro 4 passenger cars 30% lower rise in Special Tax than non-Euro 4 vehicles 2005: "Green" vehicles—those with CNG, electric, or hybrid engines—20% road tax reduction (same as gasoline rate rather than diesel) 2003: 100% rebate on basic car price for Euro 4 taxis 2003: Additional Registration Fee (usually assessed as 110% of market value of the vehicle) exemption for Euro 4 buses and commercial vehicles
Viet Nam	2006: Import duties differentiated for vehicles based on engine size: US$ 3,000 for cars under 1,000 cc, and US$25,000 for cars over 5,000 cc

cc = cubic centimeters, CNG = compressed natural gas, CNY = yuan, NO_X = nitrogen oxides, OBD = On-board diagnostic, PRC = People's Republic of China, US$ = United States dollar, VAT = value added tax.
SourceAuthors

a. Singapore

400. Singapore introduced vehicle incentives to accelerate the introduction of Euro 4 diesel vehicles (requiring 50 ppm fuel) in the lead up to its Euro 4 vehicle emissions regulation deadline in October 2006 (Table 5.10). Taxi fleets, and to a lesser extent buses and commercial vehicles, received incentives, mainly in the form of rebates on the annual registration fee. Accordingly, oil companies in Singapore geared up to provide Euro 4 diesel for direct supply to these particular market segments. In Singapore, owners of passenger cars pay an annual registration fee of 110% of the open market value, which is the basic price of the vehicle determined by customs on import and includes the vehicle cost, insurance, and freight charges. CNG, electric, and hybrid vehicles pay only 70%. While Euro 2 taxis pay an annual registration fee of 110%, Euro 4 taxis and CNG taxis pay only 30%. Buses and commercial vehicles in

general enjoy tax advantages over passenger cars, such that Euro 2 diesel buses and commercial vehicles have an annual registration fee of 5% of the open market value, and Euro 4 and CNG are exempt. In addition, Euro 4 diesel passenger vehicles pay less fuel or special tax than Euro 2 vehicles, and CNG and electric passenger vehicles are exempt from such tax.

Table 5.10: Vehicle Taxation in Singapore

Tax/Vehicle	Customs	Annual Registration Fee	COE[a]	Fuel/Special Tax	Road Tax[b]
Passenger Cars					
Petrol	20%	110% OMV	Payable	S$0.37–$0.44/l	By formula
Euro 2 Diesel	20%	110% OMV	Payable	6 times road tax	By formula
Euro 4 Diesel	20%	110% OMV	Payable	4 times road tax	By formula
CNG and Electric	20%	70% OMV (rebate of 40%)	Payable	S$0	By formula
Hybrid	20%	70% OMV (rebate of 40%)	Payable	S$0.37 - $0.44/l	By formula
Taxis					
Euro 2 Diesel	20%	110% OMV	Payable	S$5,100	By formula
Euro 4 Diesel	20%	30% OMV (rebate of 80%)	Payable	S$5,100	By formula
CNG	20%	30% OMV (rebate of 80%)	Payable	S$0	By formula
Buses and Commercial Vehicles					
Euro 2 Diesel	Exempt	5% OMV	Public and school buses are exempt	S$0	By vehicle category
Euro 4 Diesel	Exempt	0% OMV[c] (rebate of 5%)	As above	S$0	By vehicle category
Petrol	Exempt	5% OMV	As above	S$0.37 - S$0.44/l	By vehicle category (20% less than diesel road tax)
CNG	Exempt	0% OMV[c] (rebate of 5%)	As above	S$0	By vehicle category (20% less than diesel road tax)
Electric and Hybrid	Exempt	5% OMV[d]	As above	S$0	By vehicle category (20% less than diesel road tax)

COE = certificate of entitlement, CNG = compressed natural gas, l = liter, OMV = open market value, S$ = Singapore dollar.
[a] Certificate of entitlement (COE) is the certificate required for newly registered vehicles in Singapore, the price for which is established in an open bidding system in bimonthly auctions.
[b] Vehicle road tax in Singapore is assessed on the basis of engine size with formulas for four sizes ranging from less than 600cc to greater than 3,000cc.
[c] Except Euro 4 goods-cum-passenger vehicles for which an ARF of 110% OMV applies (they do not enjoy an ARF rebate under the legislation.
[d] Except CNG goods-cum-passenger vehicles which attract an ARF of 110% OMV but enjoy an ARF rebate of 5% OMV, resulting in a net ARF of 105% OMV.
Source: Singapore Land Transport Authority.

401. Singapore primarily targeted incentives to Euro 4 diesel taxis because higher quality diesel can most effectively be introduced to fleets in early stages of phasing in the fuel (Table 5.11). In 2004 and 2005, Euro 4 diesel taxis paid only 10% of the open market value in annual registration fee (compared to the standard 110%), 30% in the first three quarters of 2006, and 70% to the end of 2007 when the rebate was phased out. Euro 4 passenger cars receive a 30% lower rise in special tax than non-Euro 4 vehicles. Singapore required the Euro 4 emission standard for all new diesel vehicles registered beginning in October 2006.

Table 5.11: Euro 4 Vehicle Incentives in Singapore, 2004–2008

Vehicle Type	Incentive	Tax Incentives/Changes for Vehicles			
		1 Jun 04 - 31 Dec 05	1 Jan 06 - 30 Sept 06	1 OCT 06 - 31 DEC 07	1 JAN 08 ONWARDS
Euro 4 Diesel Passenger Cars	Special tax	6 times the road tax	4 times the road tax		
Euro 4 Diesel Taxis	ARF rebate	100% OMV	80% OMV	40% OMV	No ARF rebate
Euro 4 Diesel Buses & Commercial Vehicles	ARF rebate	5% OMV	5% OMV	5% OMV	No ARF rebate

ARF = annual registration fee, OMV = open market value.
Source: Singapore Land Transport Authority.

b. United States

402. Incentive programs in the United States for environmentally friendly vehicles, mainly in California, have typically been structured to promote innovation in manufacturing rather than to subsidize specific technology. For example, the California vehicle emission standard established a minimum market share for low and ultra low emissions vehicles, so that companies were fined US$5,000 per vehicle for not meeting the required market share through production or the acquisition of tradable credits from other firms. In addition, the California Carl Moyer Memorial Air Quality Standards Attainment Program provides incentives up to US$140 million per year for improved vehicle emission standards. From 2002 to 2003, the program helped reduce NO_X emissions by over 750 tons through funding for 453 new engines and vehicles in Southern California. This program was expanded in 2004 to include cars and light-duty trucks. In addition, the US federal Energy Policy Act of 2005 established a number of tax incentives for the purchase of hybrid and clean diesel vehicles.

c. Germany

403. Incentives for higher standard vehicles are also available in Germany. Since 1985, there has been a large difference in tax rates on cars on environmental grounds. In 2002, Euro 4 gasoline cars were exempted up to 250 Euro, and in 2003 up to 100 Euro.[100] Diesel vehicles meeting Euro 4 standards were exempted up to 600 Euro between 2000 and 2003, and 280

[100] Friedrich, Axel. 2005. Economic Incentives and the Environment. Presented at Environment 2005: Sustainable Transportation in Developing Countries, Abu Dhabi, 29 January–2 February.

Euro thereafter. In 2005, Germany imposed a heavy duty vehicle road tax that is differentiated across different Euro standard vehicles.

404. Beyond determining which vehicle characteristics to tax, it must be determined whether the tax should be based upon acquisition (sales) or upon annual licensing and registration. Acquisition taxes may reduce turnover in vehicles, thus reducing the overall penetration of new, lower emission vehicles. Annual registration taxes, by comparison, are targeted at the costs of continued use of heavier emitting vehicles and may result in better overall air quality.

d. Japan

405. Besides offering tax incentives for more fuel efficient vehicles like hybrid electric vehicles, Japan also has a green vehicle program that since 2000 has helped introduce lower emissions vehicle. Taxes on cars with NO_X emissions equivalent to 25% of 2000 standards are reduced 50%, taxes on those with less than 50% of 2000 standards are reduced 25%, and taxes on those with less than 75% are reduced 13%. Also, 11-year-old diesel vehicles and 13-year-old gasoline vehicles are penalized with a 10% additional tax. Low emissions vehicles (those with either 25%, 50%, or 75% of 2000 standards) increased in number from 882,049 in 2000 to 2,390,762 in 2001.[101]

e. PRC

406. The PRC has also provided incentives for lower emission vehicles in Beijing, as well as for more efficient vehicles. In 2003, a 30% consumption tax exemption for automakers meeting Euro 3 was instituted, along with a 30% excise tax reduction on Euro 2 light duty vehicles in Beijing. Generally beginning in 2006, cars with engines exceeding two liters faced a consumption tax of 20%, up from 8%, while taxes on smaller cars remained unchanged or were reduced.

D. Differentiated Fuel Taxes for Cleaner Fuels in Asia

407. Differentiated product taxes and prices to support cleaner fuels are likely the most promising form of market-based government support for higher quality fuels in Asia. Other forms of incentives, such as direct subsidies for capital improvements, may also play the role they have played in Japan, for example. However, regional preferences for market rationalization and the reduction of fuel subsidies, as well as constraints on public budgets in the face of high oil prices reduce the attractiveness of direct subsidies for higher quality fuels. Incentives for clean vehicles play a direct role in reducing vehicle emissions and only an indirect role in supporting the introduction of cleaner fuels.

408. Many Asian countries have a history of differentiating fuel prices and taxes to accelerate or sustain the use of cleaner fuels. Many have introduced and retained lower prices for unleaded gasoline and have introduced and retained lower prices for CNG, LPG, and, more recently, gasohol. In the case of lower sulfur fuels and Euro standard fuels, Hong Kong, China has differentiated prices between lower sulfur and conventional diesel. PRC, Japan, and Singapore have differentiated taxes for vehicles that meet different Euro standards. Experiences

[101] Hirota, Keiko, and Kiyoyuki Minato. 2002. Comparison of Vehicle Related Taxes by Cross Section. Presented at the Better Air Quality in Asian and Pacific Rim Cities 2002 Workshop (BAQ 2002), Hong Kong, 18 December. Available: http://www.cse.polyu.edu.hk/~activi/BAQ2002/ BAQ2002_files/ Proceedings/PosterSession/48.pdf

in Asia and elsewhere in the world, as noted above, suggest a potentially important role for further use of price differences over the coming years to meet higher fuel quality standards in Asia. Nevertheless, there are important considerations for each case.

1. Differentiated Taxes and Instrument Performance

409. In theory, market-based approaches, such as product tax differences, function most effectively in market-based, open economies. Adequate performance of economic instruments in general requires functioning markets, defined and enforceable property rights, fiscal structures, controlled inflation, efficient and transparent circulation of information, general acceptance of the polluter pays principle, and non-monopolistic conditions. Tax modifications, such as those described above, may not perform as well in non-competitive markets. In the case of Hong Kong, China, which imports its refined products in an open and competitive market, the HK$0.89 incentive in 2000 triggered a rapid shift to ULSD over the period of one summer. Similarly, the decision to increase the tax advantage for ULSD in the UK from 2 to 3 pence per liter in 1999 appears to have been sufficient to trigger investments among all suppliers, years ahead of regulation deadlines. As Table 5.2 indicates, many Asian countries have state-owned oil and refining sectors (although this appears to be changing). In these countries, soft budgeting practices, subsidies, and the lack of competition may make moderate tax modifications ineffective or less efficient in stimulating investments.

410. In Hong Kong, China; Japan; Sweden; and the UK, prices are also characterized by open market pricing systems and high tax regimes. Beyond the issue of instrument performance is the issue whether or not there is a sufficient tax margin to make a difference. Quite simply, countries with very low tax margins or subsidies on fuel may not have sufficient tax margins with which to influence preferences for different products in the same fashion as outlined above. Also, any type of tax modification that leads to revenue loss in low tax countries will potentially constitute a relatively large diminution in tax revenue. This issue is not nearly as significant in countries with large tax margins on fuel products. In Sweden, for example, losses in tax revenue due to the tax differential on ULSD were approximately ECU100 million, a relatively small amount when considered against the ECU18.5 billion total in taxes collected on fuels during that same period.

411. Asian countries with state controlled pricing, low taxes, or subsidies are not necessarily unable to provide some form of pricing incentives to refiners, motorists, or both for higher quality fuels. In fact, countries with price control practices might be seen as having the strong state-administered levers necessary to implement price differentials for cleaner fuels, although the economic performance of such an approach is perhaps less reliable. Similarly, countries with subsidies on fuel can differentiate or increase subsidies in an analogous manner to differentiated taxes to support lower sulfur fuels, as Indonesia has done to support unleaded gasoline. Likewise, retail prices on gasoline and diesel in Beijing were raised by a greater margin than in other cities in the PRC to compensate refining companies for the increased cost of providing Euro 3 in Beijing.

412. Over the medium- to long-term, phasing out distorting subsidies and improving efficiencies can improve the attractiveness of cleaner fuel investments, as was noted above. In principle, open markets and free prices are seen as necessary preconditions for generating capital, generating opportunities for imports, and allowing refiners either to pass costs of cleaner fuels onto motorists or demand market prices for their products. Nevertheless, to help introduce cleaner fuels over the short term, governments should take advantage of existing regimes and practices in the country.

2. Differentiated Taxes and Finance

413. Tax differentials can be designed, in theory, to be revenue-neutral across fuel grades if the government adjusts the differential to maintain constant revenues based on consumption. Hong Kong, China's phased use of a tax differential to introduce unleaded gasoline in 1991 was apparently revenue neutral, as was true with the introduction of LSD in European countries, such as Denmark. In some cases, however, there may be a revenue gain, as when Singapore in 1991 raised its tax on leaded gasoline by 12 cents. Lastly, administrative costs are generally low, as the fuel duty is collected through established procedures and a few collection points.

414. It appears that in most instances (at least those reviewed above) that tax differentials do, in fact, result in missed public revenue, notwithstanding the likely net gains in overall public benefits. The UK's £.03 per liter tax reduction resulted in an estimated loss in revenue of approximately £400 million per year. In Hong Kong, China, the reduced tax on ULSD, HK$0.89 per liter, was not replaced by higher taxes on other fuels and continues to be a revenue loss. Considering the tight fiscal position of many Asian countries, tax policies that reduce revenue may not be feasible, especially in a period of high international oil prices. Still, such initiatives can remain viable. Pricing incentives on CNG in Bangladesh are maintained despite high international prices at an estimated cost of approximately US$300 million per year. Thailand's successful use of an excise differential for unleaded gasoline in the early 1990s was due in part to the surplus status of the Thai oil fund and to low world oil prices at the time. Conversely, the Thai oil fund has run a deficit in recent years, including an B80 billion deficit in 2005. Yet, recent tax breaks for gasohol are planned to be financed from the Thai oil fund. Likewise, Nepal has maintained a subsidy for LPG at a loss to the Nepal Oil Corporation.

3. Differentiated Taxes and Political Acceptability

415. Fuel tax changes require support within the government and among the public. Decisions to alter fuel taxation are often resisted within governments because of the highly political nature of such taxation. It may be particularly challenging to use fuel taxation as an instrument for environmental goals during high oil price volatility or economic downturn. Tax and pricing policies generally require close cooperation between ministries of environment and ministries of finance, as well as between the government and private oil companies. It is the finance ministry that will ultimately be responsible for implementing the tax change, although the political basis will likely come from either the environment or health ministry. In the case of Hong Kong, China's ULSD tax, the finance ministry was initially opposed to the tax incentive, and the final decision to implement the tax came from the most senior levels of Government. One reason for Japan's use of direct subsidies to refiners to accelerate lower sulfur fuels has been to avoid the political negotiations often required for modification of fuel tax regulations.

416. Price differences at the pump may be met with public resistance. Although general price increases are almost always met with resistance (as seen in Indonesia and, more recently, Malaysia), differential pricing between fuel substitutes is likely to meet with resistance if the lower priced fuels are either seen to benefit groups that drive the newer cars for which the fuels are required or to be incompatible with certain vehicles. This has been a problem when the public has believed that unleaded gasoline could not be used safely in older cars due to concerns over valve-seat recession. In South Africa, public resistance over this issue led to the reversal of a tax incentive for unleaded gasoline. This is largely an issue of educating the public as there are no major technical problems associated with unleaded gasoline in older vehicles. Proper awareness-raising campaigns can overcome public resistance toward new, higher

quality fuels. In Hong Kong, China and the UK, citizens and civic groups were well aware of the benefits of lower sulfur fuels and many, in fact, were involved in their promotion, especially in the UK.

417. The overall political currency of fuel tax adjustments within governments and among the public will depend partially on the accuracy of knowledge about the emissions benefits of cleaner fuels, as well as the level of awareness in society of the importance of fuel quality for air quality and public health. Public awareness-raising; the availability of local scientific analyses of air quality, health, and fuel; and a strong role for civil society activity will enhance the political feasibility of adjusting fuel taxes.

E. Conclusion

1. Regulations Are the Most Important

418. Global experience shows that regulations are instrumental in establishing the market for cleaner fuels. The global phase-out of leaded gasoline and the reduction of sulfur levels in gasoline and diesel are good examples of the importance of regulations. Tax advantages and incentives have helped to accelerate the introduction of cleaner fuels, but they have not substituted for the certainty and results associated with fuel specifications and regulations.

419. In countries with refining industries, incentives may form part of the public sector stance to force tighter regulations. This may be particularly important in countries with domestic refining sectors. Experiences such as that of Viet Nam show that incentives are not necessary where the political will exists to implement tighter standards. Also, where controlled pricing regimes make local investments in cleaner fuels unattractive, industry has still been able to meet tighter specifications through imports, as India’s and the Philippines’ experience with lower sulfur fuels shows.

2. Short-Term Pricing and Tax Measures Can Be Undertaken to Foster Cleaner Fuels Regardless of the Pricing Regime in Place

420. Market pricing allows refiners to recover capital costs by passing the higher costs of cleaner fuels on to consumers. Over the long term, this may well be the most important fuel pricing policy for the introduction of cleaner fuels. High international prices in recent years have illustrated the unsustainable nature of subsidized fuel prices in general. Likewise, differential pricing for automotive fuel standards and pollution characteristics should factor into longer term fuel pricing policy discussions.

421. Over the short term, however, more immediate tax and pricing measures can be adopted to expedite the introduction of cleaner fuels. Measures that offer incentives for cleaner fuels can follow these larger shifts in pricing regime reform. Subsidies and pricing formulas can differentiate between fuels in countries with greater state control, or an incremental approach can be developed for specific locations. For example, retail fuel prices in the PRC were allowed to increase to a greater degree in Beijing in 2005 to allow refiners greater flexibility in meeting more stringent Euro 3 standards there. In any case, industry should be provided sufficient time to plan and carry out the investments necessary to retrofit its entire supply chain to ensure a smooth transition.

422. Fuel and vehicle price and tax differentiation are the main instruments to consider. Direct subsidies, such as that introduced in Japan for LSD, may not be appropriate either given the

levels of efficiency in many countries or the feasibility of subsidies with higher international prices. The design aspects and impact will vary from country to country.

VI. TIMING AND APPROACH IN THE INTRODUCTION OF CLEANER FUELS IN ASIA

A. Introduction

423. Cleaner fuels will play an important role in reducing vehicle emissions and improving urban air quality in Asia. Fortunately, most Asian countries have begun to plan for the introduction of cleaner fuels in conjunction with more stringent new vehicle standards, with the objective of reducing mobile sources emissions. The observations and recommendations set forth in this chapter are intended to support the dialogue and discussion already occurring throughout Asia, as well as to help develop a dialogue on fuel road maps in those countries where there has not to date been a substantial one. Setting the agenda for cleaner fuels and vehicles will require consultations and trade-offs among different stakeholders and agendas. This report and the recommendations in this chapter are aimed at strengthening the environmental dimension of these dialogues, thereby promoting environmentally responsible decisions and actions on fuels and vehicles.

424. A very high priority for Asia will be to complete the phase out of leaded gasoline in those countries where leaded gasoline is still available in the market.

425. As this report notes, several countries in Asia have already largely decided on the substance and schedule for future fuel specifications. Thailand stated its intention in 2004 to have Euro 4 type fuels in 2010, but had to postpone it to 2012 because of concerns about availability, with the goal of exceeding these requirements shortly thereafter and introducing ultra low sulfur fuels with less than 15 ppm sulfur.[102] Hong Kong, China; Republic of Korea; Singapore; and Taipei,China either already have Euro 4 similar fuels or will shortly have them.[103] At the subregional level, discussions have been conducted through the coordinated efforts of a working group formed under the AEM-METI Economic and Industrial Cooperation Committee (AMEICC). The members of AMEICC are the Association of Southeast Asian Nations (ASEAN) economic ministers, and the Ministry of Economy, Trade, and Industry (Japan). Through the working group, representatives from the Japanese and ASEAN vehicle industry, as well as ASEAN governments, are moving to adopt a flexible non-binding framework in which ASEAN member countries committed to introduce Euro 2 equivalent emission standards by 2006 and Euro 4 equivalent emission standards by 2010–2012. This accords with the sulfur levels agreed upon by the United Nations partnership for clean fuels and vehicles, which set a goal of 50 ppm sulfur or less in gasoline and diesel worldwide.

426. Individual oil companies have already started to develop capacity to produce 50 ppm sulfur diesel even without the formal requirement to do so. Petron in the Philippines and Reliance in India either are already producing ULSD or are soon to do so.

427. Fuel quality regulators are driven by multiple considerations. In addition to concerns about poor air quality and related costs to society, they must consider energy security, industrial policy, and the macro economy. Hence, decisions on the introduction of cleaner fuels should be based on a broad dialogue among all stakeholders. New vehicles with advanced emission control devices will provide the main benefits from reducing emissions to be realized from the

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[102] Thailand has since delayed introduction of Euro 4 vehicle emission standards with 2 years to 2012.

[103] These fuels are equivalent to Euro 4 in sulfur content but could have higher aromatics, benzene, olefins, or RVP and should not be characterized as equivalent in terms of emissions, driveability, engine wear, and fuel efficiency.

introduction of cleaner fuels. Considering the rapid motorization in many Asian countries, the sooner cleaner fuels and vehicles become available, the fewer relatively dirty vehicles there will be in Asian cities.

428. Asia's future fuel mix will be more diversified, with alternative fuels such as CNG, LPG, and biofuels having a larger market share. Such alternative fuels can play an important role in reducing air pollution caused by the transport sector. The consensus among experts, however, is that gasoline and diesel will continue to constitute the bulk of transportation fuels in Asian cities over the next 10–15 years.[104] Thus, it is important that policy makers develop and agree upon future standards for gasoline and diesel. Following a period in which no new refining capacity was created in Asia, the surging demand for transportation fuels has resulted in additional demand which can no longer be met by existing refining capacity. The need to create new refining capacity or to upgrade or expand existing refineries provides fuel regulators with a window of opportunity to shape the future refining structure in Asia that they should not pass over.

429. If policy makers in Asia intend to continue to promote diesel as the preferred public transport fuel by maintaining incentives, they should ensure that they promote "clean" diesel and not "dirty" diesel. From the viewpoint of climate change mitigation, the preference for diesel might be wise given the higher combustion efficiency of diesel and the resulting lower CO_2 emissions. In addition, some countries may be interested in increasing the deployment of more efficient diesel vehicles to decrease oil imports as part of an energy security strategy. However, these climate benefits may be lost if the diesel fuels and vehicles are not very clean, as black carbon emitted from diesel vehicles may have a high global warming potential. Pursuing such synergies between fuel quality strategies, urban air quality management strategies, and climate change mitigation strategies can help to strengthen the support for all three objectives and improve the chances for their successful implementation. Fuel specifications influence emissions but they also influence driveability, engine-wear, and fuel efficiency, which is important in terms of impact on greenhouse gas emissions.

430. The following factors will need to be considered in developing road maps for Asian countries.

B. Integrated Approach

431. Fuels and vehicles are an integrated system and should be dealt with as such. The fuel-vehicle relationship within a wider air quality context needs to be considered. The specific air quality context in a country or city can influence detailed formulation and implementation of cleaner fuel regulations. Taking into account the international experience outside Asia and in selected Asian countries, the nature and severity of air pollution in the majority of Asian cities and the absence of detailed emission inventories and source apportionment studies should not prevent Asian countries from deciding on a road map for cleaner fuels. In parallel with implementing agreed upon fuel road maps, Asian countries should continue to strive to improve the frequency and quality of detailed emission inventory and source apportionment studies. This will help to further refine the planning and implementation of integrated vehicle emission reduction strategies.

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[104] ADB. 2006. *Energy Efficiency and Climate Change Considerations for On-road Transport in Asia*. Manila. Available: http://www.adb.org/Documents/Reports/Energy-Efficiency-Transport/default.asp

432. For example, the EU, Japan, and the United States have all adopted coordinated fuel and vehicle standards. By contrast, the PRC has adopted a road map for new vehicle standards that sets a schedule for introducing Euro 3, 4, and 5 (for heavy duty vehicles only) standards in 2008, 2010, and 2012, respectively. However, it has yet to adopt a companion road map for clean fuels. Failure to do so will either delay the vehicle standards or increase, perhaps substantially so, in-use emissions.

C. Fuel Specifications

433. Which fuel parameters need to be regulated? Is there a model that can be followed so that Asia does not have to begin from basics?

434. Asian countries can benefit from the fact that they lag behind the EU and other parts of the world and can base their decision making on fuel quality research and refinery advances implemented in the EU, Japan, and the United States. As Chapter 2 details, extensive research has been conducted in support of the development of these standards. The development of vehicle emission and fuel standards is based not only on emission reduction potential but on factors such as driveability, engine wear, and fuel efficiency. Few Asian countries will have the resources to duplicate this supportive research. Australia is one country in the Asia and Pacific region that, while deciding to base its fuel standards on Euro specifications, also conducted additional research to set specific standards.[105]

435. As Asian countries have indicated a preference for Euro emission standards, they should, where possible, implement all fuel parameters as defined in the fuel specifications linked to the various Euro emission standards. This will optimize emissions reduction, driveability, engine wear, and fuel efficiency. One area where Asian countries can vary, however, is with RVP, taking into account local climatic conditions and requirements to blend biocomponents such as ethanol.

436. For properties where there is potential for deviation from the Euro 4 standards (RVP, olefins, aromatics), experts should evaluate those standards and alternatives to determine the emissions increases and the air quality penalties associated with the relaxation of the standards. This will enable decision makers to choose the strategy that best minimizes environmental damage. This approach is similar to that in Australia and the United States, where, when industry proposes a relaxation of the standards, an evaluation is performed to determine the optimal path. There might be circumstances, however, where the implementation of such a comprehensive set of fuel properties would significantly delay the introduction of cleaner fuels. In such cases, decision makers will have to balance the benefits of, for example, reducing sulfur levels with the costs of not addressing other fuel properties at the same time.

437. The phase-out of leaded gasoline, which has been completed in almost all Asian countries, has raised the issue of using other octane-enhancing metallic additives and oxygenates in gasoline. This issue should be considered in the context of the global experience in addressing the health impacts of leaded gasoline. Many Asian countries have no regulations

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[105] Australian Government, Department of the Environment and Water Resources. 2005. *Setting the Standards*. Available: http://www.deh.gov.au/atmosphere/fuelquality/standards/setting.html Australia committed to selectively aligning with Euro specifications by which each parameter would be subject to a benefit analysis based on a need to regulate and then the degree (i.e., required specification level to achieve the desired result) of regulation versus air quality.

in place for major categories of metallic additives such as MMT, or oxygenates such as MTBE, ETBE, and ethanol.

438. Asian countries deciding to regulate the use of metallic additives and oxygenates should consider the effects of combusting these additives on (i) vehicles and vehicle emissions, (ii) public health, and (iii) the technical alternatives to produce gasoline with required octane levels. These issues are discussed in detail in Chapter 4.

439. Asian countries are urged to improve the regulation of metallic additives and oxygenates. Experience from the EU, Japan, and the United States shows that metallic additives were most frequently used in older refineries, and that new refineries and refineries that are upgraded can be more readily configured to avoid the use of metallic additives. As new refineries are built or old ones expanded in Asia, they should be configured in a manner to avoid the use of metallic additives.

440. Other options, by order of preference, are blend-stock selection and the use of certain oxygenates. The use of MTBE, ETBE, and TAME should, however, be limited to maximum allowable concentrations of 2.7% (mass O_2), and 15.0%, 17.1%, and 16.6%, respectively, by volume. Regulations should specify appropriate storage facilities and handling as the means to avoid groundwater contamination. Ethanol blending should be limited to 10% by volume and 3.7% by mass. This will help ensure that air quality is not significantly affected and will protect fuel system components.

441. Prominent health experts have raised serious concerns regarding the potential adverse health effects of metallic additives such as MMT and ferrocene, as well as the potential adverse effects on vehicle emissions and emission control system components. The majority of Asian countries will lack the capacity and resources to replicate such comprehensive health impact studies. Before they authorize refiners to begin using MMT, they are advised to take note of the final results of the Health Canada study on the health impacts of manganese and the US EPA assessment of the continuing applicability of the current risk evaluation of MMT in gasoline. Asian countries should take the environmentally responsible approach to metallic-based additives and apply the precautionary principle for these additives and discourage their use until and unless the scientific and health studies show that they are safe.[106]

442. The recommendation to apply the precautionary principle for the use of metallic additives takes account of the four main criteria of the precautionary principle and its use as outlined in the Rio Declaration on Environment and Development:

(i) **Threat of serious or irreversible damage.** As Chapter 4 concludes, there is substantial concern about the negative, often chronic, health effects of metallic additives, as evidenced by a growing body of scientific literature on chronic effects. The evidence is also growing of the harmful effect of metallic additives on the performance of catalysts and OBD systems, and the concurrent serious harm in exposing the general population to harmful emissions resulting from malfunctioning catalysts.

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[106] United Nations Environment Programme. 1992. *Rio Declaration on Environment and Development.* Principle 15. Available: http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=78&ArticleID=1163. The precautionary principle states: "In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

(ii) **Lack of full scientific evidence.** Additional studies and testing, such as that required by US EPA, continues on the health impacts of metallic additives. In the case of the United States, less than 1% of fuel contains very low levels of MMT, and MMT is undergoing testing. These conditions have created a situation where there is no immediate need to take action such as applying the precautionary principle. Formal rulemaking can await the results of ongoing studies. In Canada, where additional studies had been planned, refiners have voluntarily stopped the use of MMT, thus lessening the need for such studies. Following the phaseout of leaded gasoline in Asia, fuel quality regulators considering policies on the use of octane enhancing additives are exposed to lobbying by the retailers of both metallic additives and oxygenates. Yet, the capacity to implement detailed risk assessment studies to assess health exposures and the impact on vehicle emission control systems is much more limited in these countries. In addition, the scientific evidence from the developed world is not conclusive.

(iii) **Postponing cost-effective actions.** As Chapter 4 shows, refiners have alternatives for producing gasoline with sufficiently high octane levels. High quality gasoline has been achieved across the world using a combination of refinery configurations, refining processes, and oxygenate-based additives.

(iv) **Prevention.** The use of the precautionary principle is especially relevant in Asia, where rapid motorization is resulting in increased demand for gasoline. Following years of stagnation, the expansion of existing refineries and the construction of new refining capacity has increased significantly. A strong signal should be sent to Asian regulators to ensure that the construction of new refining capacity minimizes the need for the use of octane enhancing additives, especially metallic-based additives.

443. If Asian countries decide to authorize the use of MMT, ferrocene, or other ash-forming, metallic-based additives to raise octane, they should do so on a refinery-by-refinery permit basis, with clear deadlines for phasing out the use of these additives while ensuring that they are used in limited concentrations. The decision on the use of metallic additives should be taken by regulators and should not be left to individual refiners.

444. Asian governments are encouraged to ensure that fuel quality standards reflect at least the quality of fuel as sold in the market. This is especially so in countries that have not yet adopted Euro 2 equivalent fuel standards but where the fuel marketed is already of a quality equivalent to Euro 2.

445. Some Asian countries have stated their intentions to bypass Euro 3 emission standards and move directly to Euro 4 standards. The adoption of the AMEICC framework for fuel quality improvement is likely to result in more ASEAN countries bypassing the Euro 3 phase.

446. In Asian countries where the air pollution problem is projected to be severe, decision makers should consider incorporating into their individual road maps an indication of the potential to implement Euro 5 standards at a future date. Such an indication may help refiners plan.

447. Although it is assumed and recommended that Asian countries use Euro fuel specifications, regulators might want to consider applying flexibility similar to that in US regulations. Flexibility provisions could reduce operating expenditures and ensure availability of supply, but they should be carefully designed so as to avoid erosion of benefits. All fuel properties should be considered in an integrated manner to decide costs and benefits. Until

such an integrated analysis has been conducted, no individual fuel property should be singled out when considering a flexibility provision.

448. The adoption of stricter fuel standards should be accompanied by increased, careful monitoring of fuel quality and by stricter enforcement of fuel quality standards. As emission and fuel standards become stricter, fuel adulteration becomes an increasingly important concern. Adulteration with kerosene and with lower grade fuels especially need to be monitored. Fuel quality monitoring is particularly important where different fuel standards exist within the same country.

D. Timing the Introduction of Cleaner Fuels

449. To meet the requirements outlined above, the installation of new process units and expansion of existing units would be required at most of the older refineries in Asia. The technologies involved in the production of cleaner fuels are well established and can be applied in Asia without any risk. The EU, Japan, and the United States have extensive experience modifying refineries to produce cleaner fuels. Actual experience indicates that approximately 4 to 6 years are required for extensive refinery modifications, or the construction of new refineries, for the production of cleaner fuels (Euro 4 or stricter), with about 1 to 2 years for financing and engineering, another 1 to 2 years for permitting, and about 2 years for construction. An additional year may be required for contingencies. A significant portion of the total time is needed for permitting, financing, and public input. To the extent that this portion is expedited, a shorter compliance time may be sufficient. Refineries requiring fewer modifications will, of course, require less time. Installations for a limited number of properties such as sulfur content or retrofits of existing equipment would require less construction, and the time for compliance could be reduced accordingly.

450. Tremendous refinery expansion is underway throughout Asia, with the PRC and India leading the way. These new, expanded, or upgraded refineries can reduce the overall costs or incremental time to meet Euro 4 or better fuel specifications without a need for metallic additives.

451. In addition, the technology for producing Euro 4 compliant vehicles is well established in Asia. A number of companies in Asia already manufacture Euro 4 and Euro 5 compliant vehicles, and there are companies outside Asia that manufacture such cars for export to Asia. Euro 4 vehicle emission standards for new vehicles can be introduced well within the time required to establish or modify refineries.

452. The technology is now available to retrofit gross polluting diesel vehicles, and Asian countries can consider the implementation of retrofit programs in cities with PM problems caused by diesel vehicles. Preference should be given to retrofitting fleet vehicles such as urban buses. Considering the relatively long lifetime of vehicles in Asia, retrofitting might be a viable option for some time to come. Prime candidates for retrofitting are high-use, well-maintained vehicles that are compliant with at least Euro 2 standards, mostly public transport and commercial vehicles. Retrofitting of in-use vehicles should be balanced against the accelerated phase-out of old vehicles, especially those which are pre-Euro 2 standards and for which retrofits with the most advanced technology can be difficult.

E. Scenarios for Introducing Cleaner Fuel Standards

453. Provided that the specifications are strict enough, the uniform introduction of cleaner fuel across an entire country has clear advantages for air quality. This scenario has higher short-

term costs for the refining industry, but it also avoids misfueling and reduces the resources and complexity needed for monitoring compliance. To allow flexibility, special provisions may be implemented for special markets such as off road vehicles, stationary equipment, others.

454. In especially large countries such as the PRC and India, a system of differentiated (two grades) fuel quality for different parts of the country offers another approach. Cleaner fuels are required for certain metropolitan areas, with a different quality for the rest of the country. Such an approach requires the availability or the installation of a segregated fuel marketing and distribution system. An extensive fuel monitoring system and an associated enforcement mechanism are also required to avoid misfueling and ensure compliance. Price differentials could be established to ensure that the cleaner fuel is priced more favorably than the relatively dirty fuel.

455. Harmonized introduction across Asia or subregions will have clear advantages for the regional oil companies, as well as for the vehicle industry. From the standpoint of regulation, a harmonized approach increases security in the supply of cleaner fuels.

F. Facilitating the Introduction of Cleaner Fuels in Asia

456. Fuel quality regulations, combined with vehicle emission standards, should be the foundation of any policy, strategy, or legislation to promote the introduction and adoption of cleaner fuels. Experience has shown, however, that governments can accelerate the production of cleaner fuels and their uptake by the market through a combination of tax and pricing policy, public outreach, and consensus-building. The specific means adopted and their effectiveness will be determined by whether the country is a refining or importing country, by its market orientation, and by whether subsidies are in place. Temporary incentives such as fuel product tax differentiation can be used to accelerate fuel uptake ahead of regulations. Incentives for strict vehicle standards that require cleaner fuels are also measures to stimulate the market for cleaner fuels in the early stage of implementing regulations.

457. The cost for producing cleaner fuels should be passed on to the consumer. However, controlled pricing regimes in many Asian countries tend to preclude opportunities to pass higher costs of cleaner fuels onto consumers. Still, high international oil prices in recent years have forced many governments to begin dismantling entrenched fuel subsidies and price controls.

458. Intensified awareness-raising at the national and subnational levels is important in making the case for cleaner fuels. Such campaigns should be directed toward the general public and specific groups of decision makers. The messages should focus on the role of fuels in causing air pollution and the technologies available to produce cleaner fuels, the health effects of vehicle emissions and the potential for cleaner fuels to reduce these emissions, and the overall costs and benefits of each of these elements.

459. The road map report promotes the adoption of cleaner fuels for their benefit to the environment and public health. The environment is an integral part of the mandate of bilateral and multilateral development organizations. The health impacts of cleaner fuels and vehicles are obvious and well documented. In a number of countries, governmental organizational capacity is limited, and there is both a lack of administrative and legal expertise and limited compliance monitoring capacity. As a result, implementing cleaner fuel and vehicle standards is often not done in a timely or effective way. Based on this, development organizations can and should consider assistance for the introduction of cleaner fuels. Such an assistance would consist of

(i) Capacity building for regulators to formulate, implement, and monitor fuel quality improvement strategies and legislation.

(ii) Loans or partial guarantees for refinery upgrading or new construction.

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