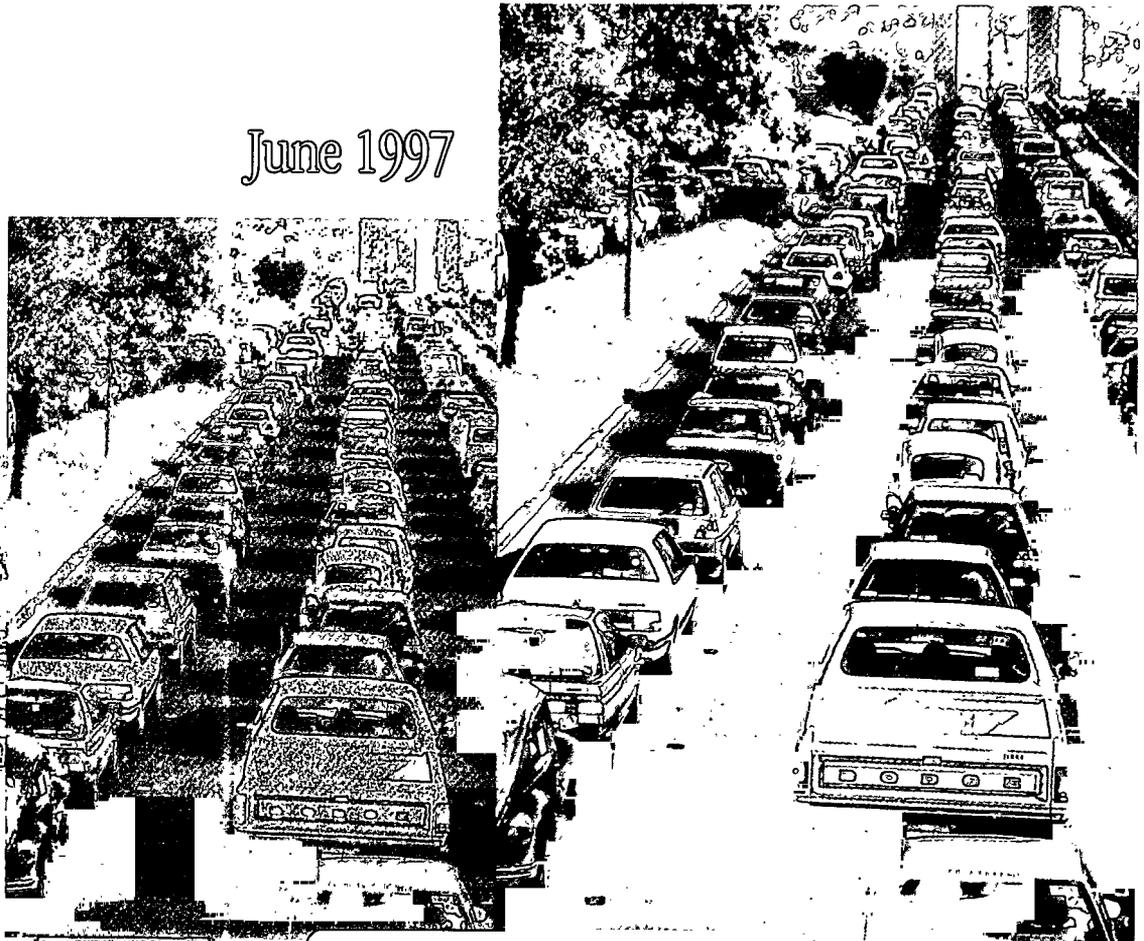


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CLEAN FUELS IN ASIA

June 1997



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Michael Walsh
Jitendra Shah

Technical Options
for Moving Toward Unleaded
Gasoline and Low-Sulfur Diesel

Metropolitan Environmental Improvement Program

CLEAN FUELS FOR ASIA

**TECHNICAL OPTIONS FOR MOVING TOWARD UNLEADED GASOLINE AND LOW-SULFUR DIESEL
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1818 H Street, N.W.
Washington, D.C. 20433 U.S.A.

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Printed in the United States of America
First printing July 1997

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The cover design is by Beni Chibber-Rao, Graphic and Map Design Section, General Services Department, The World Bank.
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FOREWORD

Air pollution has become a serious issue in many Asian cities. A major cause is the expanding motor vehicle population—with growth rates as high as 23 percent in rapidly growing economies such as China. Policymakers in Asia are beginning to review options to deal with vehicular pollution reduction. Experience worldwide has shown that the use of clean fuels—low-lead or unleaded gasoline and low-sulfur diesel—is a cost-effective way of reducing vehicular emissions.

The use of cleaner fuels in conjunction with catalytic converters would limit the total amount of emissions, thus reducing damage to human and ecosystem health. Its use would also lead to lower costs in terms of vehicle maintenance and efficiency for the individual owner.

This report describes strategies, incentives, and methods to increase the use of clean fuels. It provides policymakers with a range of alternatives that can be employed to develop a clean fuel strategy. We hope this report will assist

policymakers to make informed choices among technical and financial options available for designing a clean fuels program that could ultimately improve Asian cities' air quality significantly.

The Metropolitan Environment Improvement Program (MEIP) facilitated the preparation of this publication by providing the authors with financial support, background data, and links to Asian cities participating in MEIP. We hope that this report will be widely used by decisionmakers in MEIP cities and in other cities throughout Asia.



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PARTNERS AND CONTRIBUTORS

We would like to acknowledge the groups and individuals who contributed to this report and the promotion of clean fuel options in Asia. Core funding was provided by the United Nations Development Programme, the Australian Consultant Trust Funds, the Belgian Consultant Trust Funds, the Netherlands Consultant Trust Funds, the Royal Norwegian Ministry of Foreign Affairs, and the Norwegian Consultant Trust Funds. Inputs to this report were provided by Katsunori Suzuki and Sonia Kapoor of the World Bank, and host governments and city administrations.

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In the World Bank's Asia Environment and Natural Resources Division, the Clean Fuels report was managed by Jitendra Shah, under the ad-

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ABBREVIATIONS AND ACRONYMS

AQG	Air Quality Guideline	NH₃	ammonia
AQIS	Air Quality Information System	NMHC	non-methane hydrocarbons
AQMS	Air Quality Management System	NO_x	nitrogen oxides
BHP	brake horsepower	NO₂	nitrogen dioxide
BaP	benzo(a)pyrene	OECD	Organization for Economic Cooperation and Development
BTU	British Thermal Unit	PAHs	polynuclear aromatic hydrocarbons
CARB	California Air Resources Board	Pb	lead
CDC	Centers for Disease Control (U.S.)	PM	particulate matter
CNG	compressed natural gas	PM₁₀	particulate matter 10 microns or less
CO	carbon monoxide	ppm	particles per million
DDT	dichloro diphenyl trichloro ethane	PNA	polycyclic nuclear aromatics
ETBE	ethyl tertiary butyl ether	RFG	reformulated gasoline
EGR	exhaust gas recirculation	RVP	Reid vapor pressure
EU	European Union	SO₂	sulfur dioxide
EV	Electric vehicle	SOF	soluble organic fraction
FCC	fluid catalytic cracking	SPM	suspended particulate matter
FTP	Federal Test Procedure (U.S.)	TBA	tertiary butyl alcohol
GDP	gross domestic product	TSP	total suspended particulate
GEMS	Global Environmental Monitoring System	TWC	three-way catalyst
HC	hydrocarbons	UNDP	United Nations Development Program
IPCC	Intergovernmental Panel on Climate Change	URBAIR	Urban Air Quality Management Strategy in Asia (World Bank)
LPG	liquefied petroleum gas	USAID	U.S. Agency for International Development
μg	micrograms (10 ⁻⁶ grams)	USEPA	U.S. Environmental Protection Agency
mg	milligrams (10 ⁻³ grams)	VOCs	volatile organic compounds
g/m³	micrograms per cubic meter	WHO	World Health Organization
MCPA	methylchlorophenoxyacetic acid		
MEIP	Metropolitan Environmental Improvement Program (World Bank)		
MMT	methylclopentadieny manganese tricarbonyl		
MON	motor octane number		
MTBE	methyl tertiary-butyl ether		
NGO	non-governmental organization		
NGV	natural gas vehicle		
			1 gallon (U.S.) = 3.785 liters
			1 mile = 1.609 kilometers
		Note:	Except as indicated, "dollars" refers to 1995 U.S. dollars.

EXECUTIVE SUMMARY

Motor vehicles have brought increased mobility, and access to employment for greater numbers of people in Asia in the last decade. However, these benefits have been partially offset by excess urban air pollution and damage to human and ecosystem health. Asian countries can no longer ignore air pollution, and must begin to design comprehensive air quality management systems. These systems should encompass not only transport policy but also large industries, small enterprises, and domestic sources of pollution.

This report focuses on the abatement of vehicular pollution through the use of cleaner fuels such as unleaded gasoline and low-sulfur diesel. It aims to provide decisionmakers with a methodology for making informed choices concerning the production and use of cleaner transport fuels for motor vehicles. Transport demand management, inspection and maintenance, and advanced vehicle technology are the other components of a vehicle pollution prevention program.

The report recommends the following prioritized policy options:

1. **Adopt a strategy for the progressive elimination of lead from gasoline.** Using unleaded gasoline and catalytic converters also leads to reductions in other major pollutants such as hydrocarbons, carbon monoxide, and nitrogen oxides. Unleaded gasoline use should be encouraged through clean vehicle standards and by making it cheaper than leaded gasoline at the pump. The benefits of eliminating lead outweigh the costs.
2. **Reduce the sulfur content of diesel fuels.** Lowering the fuel density is also an effective

means of reducing fine particulate emissions. Other diesel fuel properties such as volatility, aromatic content, and additives may have a positive or negative effect on emissions. In addition to the adoption of mandatory limits on sulfur, tax policies can be very effective in encouraging the use of low-sulfur diesel.

3. **Encourage the use of alternative fuels.** Alternative fuels that have been proven cost-effective should be promoted through policies that encourage substitution. Conservation of oil products, energy security, and climate change or global warming are additional reasons for encouraging the use of alternatives to conventional fuels.

In addition to these three important steps, the regular inspection and maintenance of vehicles should be encouraged. Poorly maintained cars are responsible for a disproportionate amount of vehicle emissions. Semi-annual inspection and maintenance of vehicles results in a substantial reduction in particulates, volatile organic compounds, and carbon monoxide emissions. Emissions reduction can occur simultaneously with improved fuel economy and diminished need for repairs.

Asia's vehicle population is projected to continue growing well into the next century. If no action is taken now, air quality is bound to deteriorate, exacting a high toll on human health and possibly undermining many economic development gains. Based on lessons learned in other parts of the world, this report offers Asia's policymakers some valuable tools and suggestions for confronting the worsening air pollution situation now, and ensuring a cleaner environment in the future.

CHAPTER 1: INTRODUCTION

This report provides the methodology for improving air quality in large Asian cities through the use of clean fuels. This study is directed to decisionmakers whose policies have a direct impact on the production and use of cleaner transport fuels. The objective of this report is to provide a technical overview of the challenges and opportunities for lowering vehicle emissions by means of fuel modifications or substitutions. Issues receiving particular attention are **reducing and removing lead in gasoline and reducing sulfur in diesel fuel.**

BACKGROUND

In 1995, the global motor vehicle population, including passenger cars, trucks, buses, motorcycles, and three-wheeled vehicles (tuk-tuks or rickshaws) exceeded 700 million for the first time in history. While most of these vehicles remain concentrated in the highly industrialized Organization for Economic Cooperation and Development (OECD) countries, an increasing number of urbanized areas in developing countries, especially in Asia, now contain many motorized vehicles. Cities including Bangkok, Jakarta, and Seoul have some of the most congested roads in the world. While these vehicles have brought many advantages, including increased mobility and flexibility for millions of people and more jobs, and enhanced many quality-of-life aspects, the benefits have been partially offset by excess pollution and adverse effects on human health and the environment.

Motor vehicles emit large quantities of carbon monoxide (CO), hydrocarbons (HC), nitrogen ox-

ides (NO_x), and toxic substances such as fine particles and lead, as well as contributing to secondary by-products such as ozone.¹ Reducing vehicular pollution usually requires a comprehensive strategy encompassing the following elements:

- automobile demand management (incentives to reduce automobile use such as road tolls, parking restrictions, area licensing schemes, mass transit availability, etc.);
- inspection and maintenance;
- advanced vehicle technology; and
- clean fuels.

This report focuses primarily on clean fuels. It starts with a brief summary of the air pollution problem in selected Asian cities, followed by the challenges and opportunities for lowering vehicle pollution through greater use of clean or alternative fuels. The remainder of the report explores some of the pollution control efforts underway in the region.

THE AIR QUALITY SITUATION IN ASIA

Over the course of the past two decades, there has been an explosive growth in many Asian countries' motor vehicle populations. As a result, serious air pollution exposure problems caused by vehicle emissions are emerging. The section below takes a brief look at nine Asian cities.

Bangkok, Thailand

Eleven years of air quality monitoring indicate that the air pollutants of greatest concern in Bangkok are suspended particulate matter (SPM),

especially respirable particulate matter (PM₁₀)², CO, and lead, caused mostly by the transport sector. Current SPM levels in Bangkok's air, especially along congested roads, far exceed Thailand's primary ambient SPM air quality standard. In 1993, curbside 24-hour average concentrations exceeded this standard on 143 out of 277 measurement days. Mobile sources continue to be the Bangkok population's biggest source of exposure.

Beijing, China

In spite of a relatively small vehicle population, air pollution problems caused by motor vehicles have started to emerge in major Chinese cities, especially Beijing. The number of automobiles in Beijing is almost 10 percent of the total in all of China (19 million), and many Chinese-made vehicles still use 20-year old designs, resulting in CO and HC emissions rates that are 10–20 times the levels emitted by modern engines. According to an air quality survey, motor vehicles contribute about half of the total CO, HC, and NO_x emissions coming from all pollutant sources. Lead is another pollutant of concern; concentrations of lead in Beijing are 1–1.5 µg/m³, and have reached 14–25 µg/m³ in extreme cases.

Ho Chi Minh City, Vietnam

Although available air quality data are limited, the Institute of Hygiene and Public Health conducted a monitoring study in 1993. Results showed that particulates, or dust, are a very serious problem at present, and that CO and nitrogen dioxide (NO₂) also exceeded current Vietnamese standards. The study demonstrated that although many sources certainly contribute to these problems, vehicle emissions seem to dominate.

Hong Kong, China

Particulates are Hong Kong's most serious pollution problem at present, and motor vehicles are estimated to be responsible for approximately 50 percent of PM₁₀ emissions. Using the methodol-

ogy developed by the California Air Resources Board, the Hong Kong Environmental Protection Agency estimates that particulates from diesel vehicles alone cause approximately 290 premature deaths from lung cancer each year.

Kuala Lumpur, Malaysia

Based on available 1992 data, it was concluded that the air pollution problem is relatively serious in comparison with accepted air quality guidelines.³ Annual and daily PM₁₀ averages regularly exceeded guidelines, as did CO and ozone. Follow-up studies in 1994 continued to show serious problems, as particulates routinely exceeded guideline limits and appeared to be worsening. NO₂ and particulate matter were the most pervasive air pollutants, and motor vehicles were again found to be the main source of air pollution.

Manila, the Philippines

In Metro-Manila, air quality data are available, and measured concentrations of PM₁₀ routinely exceeded acceptable levels by a factor of more than three. Measured total suspended particulates (TSP) exceeded acceptable levels by even larger percentages. Lead concentrations also exceeded Government standards.⁴ Monitoring indicates that both CO and NO₂ occasionally exceed standards. Measurement for sulfur dioxide (SO₂) and total oxidants indicated concentrations, at present, were within acceptable standards. Motor vehicles were found to contribute over 40 percent of PM₁₀.⁵

Jakarta, Indonesia

During the ten-year period between 1981 and 1991, Jakarta's population doubled; there was also a tremendous rise in the number of vehicles, from approximately 900,000 to 1,700,000, making Jakarta's growth rate one of the highest in developing countries. These changes are reflected in the city's poor air quality. Overall, traffic and industry are Jakarta's main sources of air pollution. TSP emissions are estimated at 96,733 tons

per year, PM_{10} emissions total 41,369 tons per year, and NO_x emissions are calculated at 43,031 tons per year. Annual TSP averages in the most polluted areas are 5–6 times the national air quality guideline. Motor vehicles were found to contribute 40 percent or more to PM_{10} .⁶

Mumbai, India

Greater Mumbai's population grew 38 percent between 1971 and 1981, and another 20 percent by 1991, reaching 9.9 million. The expansion of industry, increased production, and a 103 percent increase in the number of motor vehicles has led to a severe air pollution problem. Diesel trucks and three-wheel vehicles contribute significantly to air pollution. The annual TSP concentration increased from $180 \mu\text{g}/\text{m}^3$ to approximately $270 \mu\text{g}/\text{m}^3$ between 1981 and 1990, an increase of almost 50 percent. Total annual emissions of TSP and PM_{10} are estimated at 32,000 and 16,000 tons, respectively, per year. World Health Organization (WHO) air quality guidelines and national guidelines for TSP are frequently exceeded in Mumbai. Of the population, 97 percent lives in areas where the WHO guideline is exceeded. Measures to reduce air pollution in Mumbai must focus on the most important source—traffic—which contributes about 50 percent of PM_{10} .⁷

Kathmandu, Nepal

Kathmandu Valley's population grew 44 percent between 1980 and 1990. In 1992, its population was estimated at 1,060,000, of which 54 percent was urban. The growth in population has been accompanied by a doubling in the number of motor vehicles in the past decade, which can be seen in increases in the use of gasoline (150 percent), motor diesel (175 percent), kerosene (250 percent), and fuel oil (580 percent) during 1980–93. Air pollution measurements show that particulate pollution is the most significant problem in the Kathmandu Valley. Total TSP emissions per year amount to 16,500 tons. PM_{10} emissions are 4,700 tons per year. WHO guidelines for TSP

and PM_{10} are often substantially exceeded. TSP concentrations have been measured at above $800 \mu\text{g}/\text{m}^3$ (WHO TSP guidelines are $150\text{--}230 \mu\text{g}/\text{m}^3$). Visibility in the Valley has been reduced substantially, which has impacted tourism, one of Nepal's major sources of revenue.⁸ Motor vehicles and scattered small brick manufacturers were found to be the largest source of human exposure to air pollution.

CONCLUSIONS

As the above examples illustrate, many major Asian cities' current air quality levels already reflect serious air pollution, with the transport sector contributing about 50 percent of PM_{10} .

Because the vehicle populations in most of these cities continue to grow, often at rates exceeding 10 percent per year, future air pollution problems will be even more serious unless aggressive control efforts are undertaken. Fortunately, several countries in the region have developed significant pollution control efforts, which are the subject of chapter 5.

ENDNOTES

1. See appendix A for a detailed review of adverse health effects associated with vehicular air pollution.
2. PM_{10} refers to particles in the size range of 10 microns or less. All of these particles are considered respirable and therefore, from the public health perspective, more important than larger particles.
3. Japan International Cooperation Agency. August 1993. "Air Quality Management Study For Kelang Valley Region."
4. The World Health Organization is sponsoring a study regarding "The Impact Of Vehicular Emissions On Vulnerable Populations In Metro Manila"; preliminary results indicate that 10 percent of school children (ages 6–14 years) have blood lead levels of 20 micrograms per

deciliter or higher. This is twice the level of concern identified in the umbilical cord study. All of the street child vendors tested (ages 6–15) had blood lead levels above 10 and many had levels over 30, an alarming statistic.

5. Larssen, Steinar et al., 1996. *Urban Air Quality Management Strategy in Asia: Metro Manila Report*. Metropolitan Environmental Improvement Program, The World Bank. Washington, D.C.
6. Grønseki, Knut Erik et al., 1996. *Urban Air Quality Management Strategy in Asia: Jakarta Report*. Metropolitan Environmental Improvement Program, The World Bank. Washington, D.C.
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CHAPTER 2: GASOLINE

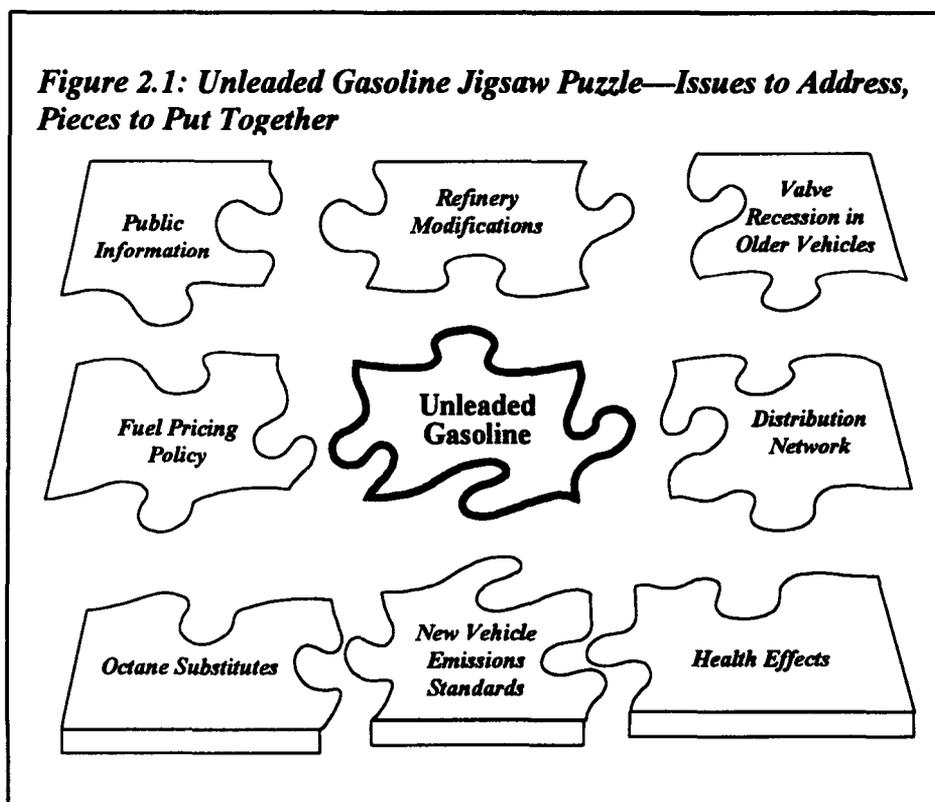
In most developing countries, gasoline consumption contributes substantially to overall vehicle emissions. The most critical issue is whether or not to reduce or eliminate the use of lead-based additives. Not many years ago, almost all gasoline used contained lead (as an octane booster), often in concentrations greater than 0.4 grams per liter. Since the early 1970s, there has been a steady movement toward reducing lead in gasoline and, increasingly, completely eliminating lead. Countries as diverse as Austria, Brazil, Japan, Thailand, and the United States have completely eliminated lead from gasoline (see appendix D for a list of international automotive emissions and fuel standards). In addition, (in 1996) over 85 percent of all new cars worldwide will require the exclusive use of unleaded gasoline to protect their emissions control systems (catalytic converters). This section of the report will review the reasons for the shift to unleaded gasoline (figure 2.1); address some of the arguments against the use of unleaded gasoline; and finally summarize other fuel characteristics used in reformulated gasolines to re-

duce overall vehicle emissions. It will conclude with recommendations for decisionmakers on how to advance the use of cleaner gasoline.

THE BENEFITS OF REDUCING LEAD IN GASOLINE

In many ways, lead is an extremely useful material. It resists corrosion and weathering, is plentiful in readily accessible areas, and is easily melted down for use. Because of these characteristics, it has been widely used by humans for

Figure 2.1: Unleaded Gasoline Jigsaw Puzzle—Issues to Address, Pieces to Put Together



centuries, in plumbing, printing, hunting, building, and more recently as electrical insulation, radiation shielding, and in paints and batteries. Lead's inertness, which makes it a useful material, however, may also lead to its relatively long environmental residence time, as indicated in table 2.1.¹

Reduced Lead Health Risks

Gasoline lead affects human health through several media, the most important of which is air. It is generally recognized that over 90 percent of atmospheric lead concentrations in most urban areas using leaded gasoline are attributable to gasoline lead emissions. Beyond this, however, gasoline lead increases the amount of lead ingested through the digestive system. This is especially true of children who not only ingest this lead through the normal food chain, but also play in lead-contaminated streets and yards. It is not surprising that "both average blood lead levels and cases of lead poisoning in children correlate more strongly to gasoline lead than to lead in the air alone."² Because of this close relationship, reducing gasoline's lead has been demonstrated in the United States to significantly reduce health

risks in urban areas. For example, based on data collected in more than 60 U.S. cities by the Centers for Disease Control (CDC) (commonly known as the *NHANES II* study), the decline in mean blood lead levels, computed by six-month intervals, almost parallels the declining amounts of lead used in gasoline during 1976-80.³

After a careful review of the *NHANES II* data, CDC's Center For Environmental Health (Dr. Vernon Houk) explained,

"This reduction was real. It was not due to chance, laboratory error, nor sampling of age, sex, race, urban versus rural areas, income levels, or geographic regions. The most significant environmental change during this time was the reduced amount of lead used in the production of gasoline... (These data) clearly demonstrates that as we have removed lead from gasoline, we have also removed lead from ourselves and our children."⁴

In the past, leaded gasoline was cited as the reason for elevated blood lead levels every summer in the United States. This was correlated to increased use of automobiles during those months. Automotive emissions are also the reason why lead levels in the front yards of urban homes are two to three times greater than in the back yards.

In Europe, the Joint Research Center in Ispra, Italy, completed a study designed to determine the relationship between gasoline lead and human uptake.⁵ The study replaced standard gasoline lead with a variant having a different isotopic ratio, in order to follow the pathway of gasoline lead through the northern Italian region of Piedmont, where the study was conducted. The study reached the following conclusions:

1. Gasoline lead is responsible for about 90 percent of airborne lead in Turin and about 60 percent of airborne lead in rural areas.
2. Gasoline lead seems to contribute the finest airborne lead particles.
3. The percent of gasoline-supplied lead in blood was 24-27 percent in Turin; 12-21 percent in the nearby countryside; and 11-19 percent in the remotest countryside.

Table 2.1: Environmental Residence Times For Various Pollutants

Pollutant	Situation	Time	Remaining (%)
2,4,5-T (herbicide)	soil	several weeks	50
MCPA (herbicide)	soil	several days	50
DDT (pesticide)	soil	4 months	74
Oil	sea water	4-5 weeks	70
Lead	soil	70-200 years	90

Box 2.1: What We Know About Lead Exposure, Past and Present

Because of lead's growing number of uses and long residence time, human lead exposure has been increasing for many generations, and will probably continue to accumulate in the future. It is now estimated that modern man's lead exposure is 100 times greater than background or "natural" levels.¹ Studies of annual arctic ice layers in Greenland also indicate the rise in lead levels over the earth's surface. At this point in history, lead has been dispersed so widely that "it is doubtful whether any part of the earth's surface or any form of life remains uncontaminated by anthropogenic lead."² More recent evidence continues to show "unambiguous evidence of the gasoline-related sources of lead in aged Greenland snow and ice."³

One of the modern world's major uses of lead is in gasoline. In 1921 it was discovered that the addition of lead to gasoline raised octane levels. This was desirable because higher octane gasolines allow higher compression ratio engines with concomitant improvements in thermal efficiency and fuel economy. However, the addition of lead to gasoline caused a whole series of problems for automotive designers, including troublesome combustion chamber deposits on pistons, spark plugs, and valves, and increased piston ring wear and blow-by rates.

More importantly, as discussed in appendix A, evidence has been accumulating that children in cities are suffering adverse health consequences when lead added to gasoline is emitted from vehicles. In addition, lead deposits within engine combustion chambers lead to higher emissions of hydrocarbons, which directly and indirectly harm health and well-being. Furthermore, the use of lead precludes the use of catalytic converters, that have been demonstrated to substantially reduce hydrocarbons and other noxious gases in vehicle exhaust. Ironically, by precluding the use of these advanced technologies, leaded gasoline may

also impair overall fuel efficiency by not allowing the use of up-to-date motor vehicle technology and more efficient pollution reduction techniques.^{4,5} In adults, blood lead is related to blood pressure increase and to cardiovascular disease, particularly strokes, heart attacks, and premature death. The monetary benefits of reducing adult illnesses would be substantial and would probably outweigh the costs.⁶

In spite of these concerns, much of the discussion regarding removal of lead from gasoline has focused almost exclusively on costs and difficulties, and little on the benefits. The purpose of this section (and appendix A) is to summarize some of these potential benefits.

Endnotes

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5. Faiz, Asif, Christopher S. Weaver, and Michael Walsh. 1996. "Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions." The World Bank: Washington, DC.
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Assessing the study, the institute's director, Dr. Facchetti, noted that the relationship between airborne lead and blood lead is relatively equal between Europe and the United States—an increase of 1 microgram of lead per cubic meter of ambient lead results in an increase of about 1–2 micrograms per milliliter of blood lead.⁶ Furthermore, the Ispra experiment probably underestimated the overall impact of gasoline lead on blood lead because:

1. Only about 90 percent of the local gasoline contained the test isotope.
2. The study only measured local effects and could not account for lead emitted and blown in from vehicles from other areas.
3. When the experiment ended, gasoline-related blood levels had not yet reached equilibrium; blood lead levels were still rising.

In adults, blood lead is related to blood pressure increases and cardiovascular disease, par-

ticularly strokes, heart attacks, and premature death. The monetary benefits of reducing adult illnesses affected by airborne lead would be substantial, and would probably outweigh the costs of reducing the lead (figure 2.2).⁷

Reduced Vehicle Maintenance

One of the greatest benefits of eliminating lead from gasoline would be the reduction in health risks, but there would be additional benefits. For example, lead-free gasoline would save motorists money by reducing the need to continuously replace spark plugs, mufflers, and other automobile hardware exposed to gasoline and its combustion products.⁸ Lead scavengers are highly corrosive and reactive; several surveys conducted when leaded gasoline was widely available in the United States and Canada demonstrated that motorists using lead-free gasoline spent much less on exhaust system and ignition servicing than motorists using leaded gasoline.⁹ As a general principal, spark

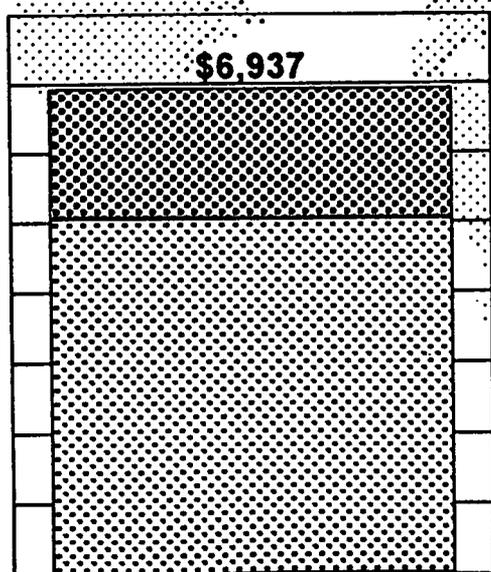
plug change intervals are usually doubled by the use of unleaded gasoline, and at least one exhaust system and exhaust silencer (muffler) replacement during the life of a motor vehicle is eliminated. Lead-free gasoline is also linked to cost advantages regarding carburetor servicing, but this has been more difficult to quantify.

Another significant advantage associated with lead-free gasoline is a lengthened interval between oil changes. Unleaded fuel has been demonstrated to significantly reduce engine rusting and piston ring wear, and to a lesser degree, sludge and varnish deposits and cam and lifter wear.¹⁰ Because of this, oil change intervals in U.S. cars using unleaded fuel have become at least twice as long as had previously been the case. Intervals of 10,000 miles are not uncommon in new cars. Increased oil change intervals cannot be attributed solely to lead removal (as is indicated by some increases in vehicles using leaded gasoline), but lead removal appears to be a contributing factor. This is significant not only

Figure 2.2: The Economic Benefits of Reducing Lead Exposure

Millions

\$8,000
\$7,000
\$6,000
\$5,000
\$4,000
\$3,000
\$2,000
\$1,000
\$0



☒ Infant Mortality
☒ Earnings Loss

1 microgram/deciliter reduction
One year's cohort of US Children
\$5,307 per IQ Point

because of the reduced cost to the motorist, but also because of oil savings over the vehicle's life, and the reduced pollution potential of the used oil. Perhaps more significant in reducing engine wear are the additive packages that are added to unleaded fuel for lubricity, as well as changes in valve ring material.

The Environment Protection Agency (Canada) studied reductions in maintenance costs attributable to lead-free and unleaded gasoline. An Australian review reported those results and found them to be significant.¹¹ Expressed as 1980 Canadian cents per liter, the results of the studies concluded (table 2.2):

A car consuming 10 liters of unleaded fuel per 100 kilometers would experience maintenance savings averaging about Can\$38 per year, or Can\$0.024 per liter of gasoline.¹²

Pollution Reduction by Emissions Converters

The U.S. Environmental Protection Agency (USEPA) studied the impact of leaded gasoline on the performance of catalytic converters in 1984.¹³ Twenty-nine in-use automobiles with three-way catalytic converter systems were misfueled with leaded gasoline in order to quantify the emissions effects. (For a review of controls on gasoline-fueled vehicles, see appendix B.) The vehicles used between four and twelve tanks of leaded gasoline (average lead content 1.0 grams per gallon). Four different test programs were conducted, with different misfueling rates and mileage accumulation schedules. The U.S. Federal Test Procedure (FTP) and several short tests were conducted at various stages. The results of the program indicated that vehicle emissions are primarily affected by the amount of lead passing through the engine, and secondarily by the rate of misfueling. In addition, lead in gasoline not only affects the performance of the catalyst but poisons it as well.

Based on the data collected, it was possible to develop quantitative relationships between lead consumption and HC, CO, and NO_x emissions. Emissions levels for each of the 29 vehicles in-

Table 2.2: Cost Savings from Maintenance Reductions with Lead-free Gasoline (1980 Canadian cents per liter)

Company	Year	Cost Savings
Wagner (American Oil Co.)	1971	1.4
Gray & Azhari (American Oil Co.)	1972	21
Pahnke & Bettoney (DuPont)	1972	0.3
Adams (Ethyl Corp.)	1972	0.4
Environment Canada	1979	1.2

Table 2.3: Additional Savings from Leaded Versus Unleaded Gasoline

Process	Leaded Gasoline	Unleaded Gasoline
spark plug changes	every year	every other year
oil & filter changes	twice per year	once per year
muffler replacements	twice per 5 yrs	once per year
exhaust pipe replacements	once per 5 yrs	none

involved in the USEPA program were normalized to the levels which existed prior to any lead contamination,¹⁴ then plotted as a function of the total amount of lead consumed. Normalization made it possible to eliminate the influence of different emissions standards. Regression equations were then derived, relating HC, CO, and NO_x emissions respectively to the grams of lead consumed by each vehicle (figure 2.3).

As figure 2.3 indicates, FTP emissions of HC, CO, and NO_x generally increased steadily with continued misfueling. HC emissions increased the most rapidly on a percentage basis, followed by

CO, and to a lesser extent, NO_x. Reasonably good correlations exist for the relationship between total lead consumed and emissions increases of each pollutant, especially for HC, one of the pollutants most affected. In the case of HC, approximately 90 percent of the variability in emissions can be explained by the lead exposure.

Figure 2.4 shows an example of the comparative cost of catalytic versus non-catalytic converters in gasoline automobiles. The extra cost of the catalytic converter can be recovered within four years or less, depending on the actual emissions reduction and maintenance, and associated health impact and other cost assumptions.

IMPLEMENTATION CONSTRAINTS ON UNLEADED GASOLINE

While the problems (health, economic, and environmental) associated with leaded gasoline have been outlined above, it is important to also outline potential hazards associated with unleaded gasoline. Lead is added to gasoline because it is a low-cost octane enhancer. If lead is not added to gasoline the refinery must either modify its processes to raise the octane level, or add alternative octane-enhancing additives, such as MMT, ethanol MTBE, or ETBE.

Figure 2.3: Impact of Lead on Catalytic Converter-Equipped Cars

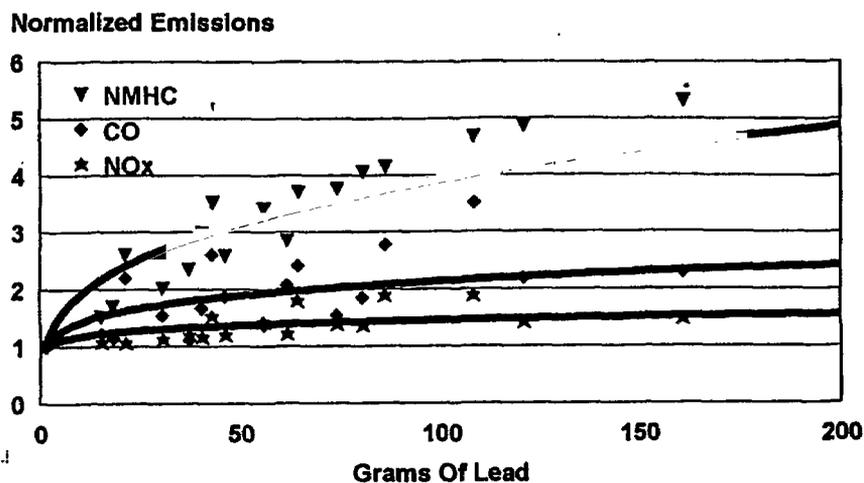
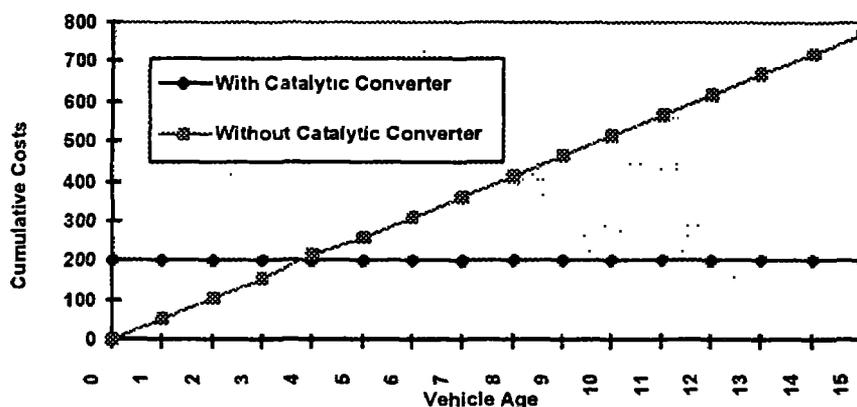


Figure 2.4: Representative Cost Comparisons Between Cars With and Without Catalytic Converters



Refinery Modification Options to Produce Unleaded Gasoline

Refinery investments are generally capital-intensive. The selection of technology to mitigate or eliminate adverse environmental impacts by fuel reformulation is a complex process. Addressing specific clean fuel reformulation characteristics for each petroleum product (if addressed individually) may add substantially to costs, compared to an integrated program encompassing gasoline,

diesel oil, and residual fuel oil. Other externalities may require a program to be fragmented.

Modifications and additions to existing refineries to meet emerging environmentally-friendly gasoline specifications could range over a wide spectrum:

- introducing changes in operating conditions in naphtha reformers to either increase octane, or reformulate or decrease aromatics production, depending on market characteristics;
- changing the crude oil supplied to the refinery;
- modifying the fractionation process; and
- introducing new processing facilities such as alkylation, isomerization, fluid catalytic cracking, hydrocracking, and oxygenate production facilities.

The strategy used will need to be project-specific and linked to desired objectives. A multi-pronged program including reduced or eliminated lead, limited benzene and aromatic levels, Reid vapor pressure control, and front-end octane improvement could include all of the process options listed above. A more modest program might need only a few of those options.

Aside from removing lead, limiting aromatics and benzene must be factored into any gasoline reformulation program. As seen in the United States in the early 1970s, when restrictions were first imposed on gasoline lead levels, the preferred option was to increase the octane number by more severe reforming of naphtha to compensate for octane lost by eliminating lead. This increased the aromatics (especially benzene) concentrations in gasoline. As the adverse health impacts of these hydrocarbons began to be known, USEPA imposed limitations resulting in the need for additional investments to eliminate the problem created by more severely reformulated naphtha.

The costs of even a modest gasoline reformulation program will be substantial. Therefore, it is important to tailor the program to meet specified environmental objectives.

Furthermore, care needs to be taken to ensure that investments do not produce undesirable secondary problems, and do not become a constraint to expanding the reformulation program as gasoline markets expand.

Valve Seat Recession

As engine technology advanced during the leaded gasoline era, motor vehicle designers used lead's friction-reducing properties to serve as a lubricant between exhaust valves and their seats, enabling them to use a lower-grade metal for the valve seats. Leaded fuel shielded the valve seats from excessive wear, or valve seat recession, which can occur at high speeds in engines without hardened valve seats. This protective function is the reason why USEPA limited gasoline lead content to 0.1 grams per gallon, rather than banning its use entirely in 1985. However, the actual incidence of valve seat recession is minuscule;¹⁵ the only vehicles even appearing to be vulnerable travel consistently at very high loads and speeds, and even in these vehicles, additives other than lead have been shown to protect valve seats. There is no technical argument to retain any lead in gasoline, if the refining capacity exists to provide the required octane in some other manner. For example, although Thailand completely eliminated the sale of leaded fuel on January 1, 1996, there has been no evidence of valve recession problems in existing vehicles. However, it should be noted that in some countries (e.g., those that manufacture cars without catalytic converters, or that import cars from these manufacturers) lack of information concerning these issues may pose a constraint to lead phaseout.

Box 2.2: Can Unleaded Gasoline be Used in Pre-Catalytic Converter Vehicles?

Yes, for most cars:

- Valve recession has not been observed under real-world conditions.
- Lead substitutes (sodium, sulfur) available if needed.
- No other impediments identified.

Potential Health Risks Associated with Lead Substitutes in Non-Catalytic Converter Vehicles

Refineries use a number of techniques to replace the octane formerly contributed by lead. As noted above, increased catalytic cracking and reforming are used to increase the concentrations of high-octane hydrocarbons such as benzene, toluene, xylene, other aromatics, and olefins. Alkylation and isomerization are also used to convert straight-chain paraffins (relatively low-octane) to higher-octane branched paraffins. Increased quantities of light hydrocarbons, such as butane, are also blended. Use of high-octane oxygenated blending agents such as ethanol, methanol (with co-solvent alcohols), and especially methyl tertiary-butyl ether (MTBE), as well as other agents, has increased greatly. In addition, the antiknock additive methylcyclopentadienyl manganese tricarbonyl (MMT) is permitted in leaded and unleaded gasoline in the United States, and a health testing program is being developed to assess MMT's and oxygenates' effects on health. MMT is also permitted in both leaded and unleaded fuel in Canada.¹⁶

Some of these solutions have created or aggravated environmental problems of their own. For example, the increased use of benzene and other aromatics (which tend to increase benzene emissions in the exhaust) have led to concern over human exposure to benzene, which is carcinogenic. The xylenes, other alkyl aromatics, and olefins produce much more ozone than most other hydrocarbons. Increased use of light hydrocarbons in gasoline produces a higher Reid vapor pressure (RVP), and increased evaporative emissions.

Most of these lead substitutes are not a serious concern if the switch to lead-free gasoline is combined with the introduction of catalytic converters. As indicated in appendix B, catalytic converters tend to be especially effective on many of the more reactive or toxic hydrocarbons. However, in order to maximize the health benefits of unleaded gasoline use in vehicles without catalytic converters, it is prudent to assure that acceptable alternatives are used.

Strategies to Reduce or Eliminate Health Risks Associated with Lead Substitutes

Low-lead gasoline as a transition fuel. Vehicles equipped with catalytic converters require unleaded gasoline so as not to destroy the converter with lead deposits. Vehicles without catalytic converters can use unleaded gasoline but do not require it. Because reducing or eliminating gasoline lead is desirable for public health reasons, one transition strategy that may be used while catalytic converter technology is being phased in is to continue to market fuel with a **minimal lead content**.

The octane boost from lead does not increase linearly with lead concentration. The first 0.1 gram per liter of lead additive gives the greatest octane boost, and subsequent lead concentration increases give progressively smaller returns. This means that two units of low-lead gasoline will produce lower lead emissions than one unit of high-lead gasoline of the same octane value, in a motor vehicle without a catalytic converter. If octane capacity is limited, the quickest and most economical way to reduce lead emissions may be to reduce the gasoline supply's lead content by as much as possible, rather than encouraging non-catalytic converter-equipped cars to use unleaded fuel. This also helps to reserve supplies of unleaded gasoline (often feasible to produce and distribute only in limited quantities) for catalytic converter-equipped vehicles truly requiring it. Reducing the permitted lead content will also reduce the refining cost difference between leaded and unleaded gasoline. If this is reflected in retail prices, it will reduce the temptation for owners of catalytic converter-equipped vehicles to misfuel with leaded gasoline. In the United States, as noted earlier, the lead content of leaded gasoline has been limited to 0.1 grams per gallon (since 1985). In Europe, the maximum lead content of leaded gasoline is 0.15 grams per liter.

Non-hazardous lead substitutes. Blending small percentages of oxygenated compounds such as

ethanol, methanol, tertiary butyl alcohol (TBA), and MTBE and other ethers with gasoline has the effect of improving the antiknock performance. Thus, the amount of lead can be reduced or even eliminated, without substituting potentially hazardous aromatic compounds.

Exhaust HC and CO emissions are reduced by the use of oxygenates, but NO_x emissions may be increased slightly by leaner air-fuel mixtures. The U.S. *Auto/Oil* study recently tested the effects of adding 10 percent ethanol (3.5 percent oxygen by weight) and adding 15 percent MTBE (2.7 percent oxygen by weight) to industry-average gasoline. For newer gasoline vehicles, the ethanol addition results showed a net decrease in non-methane hydrocarbons (NMHC) (5.9 percent) and CO (13.4 percent), and a net increase in NO_x emissions (5.1 percent). The MTBE addition results showed net decreases in NMHC (7.0 percent) and CO (9.3 percent), and a net increase in NO_x emissions (3.6 percent).

Alcohols such as ethanol tend to increase evaporative emissions and can therefore produce higher total HC emissions than straight gasoline, unless ambient temperatures are so low that evaporative emissions are negligible. Similar adverse effects have not been reported for MTBE and other ethers. Corrosion, phase separation on contact with water, and materials compatibility, other problems sometimes experienced with alcohol fuels, are much less serious for ethers. For this reason, MTBE and other ethers are strongly preferred as oxygenated blending agents by many fuel marketers as well as for air-quality purposes. The costs of using ethers are also relatively moderate (approximately US\$0.01–0.03 per liter at present prices), so these substitutes can be a cost-effective approach as well.

To summarize, it is possible to substitute certain oxygenates in place of lead to produce unleaded gasoline with maximum health benefits, no lead, and no increase in other toxic compounds. The case of Hong Kong, China (chapter 5) demonstrates how unleaded gasoline can have virtually the same aromatic content as leaded gasoline, in part due to the use of oxygenates.¹⁷

Adverse health effects with MTBE. During the winters of 1993 and 1994, a number of U.S. cities using oxygenated gasoline (as required by the 1990 *Clean Air Act*) reported cases of people suffering from severe nausea, headaches, and other symptoms. These cases were apparently linked to the exposure to MTBE fumes or its combustion derivatives. Following an intense public outcry over the use of oxygenated gasoline in Milwaukee, Wisconsin, the state ordered a study of the health effects. The first phase has been completed and the results have been summarized by several U.S. states and the USEPA (box 2.4).

Reformulated gasoline. Beyond substituting oxygenates that are less hazardous than lead, additional gasoline modifications are possible. Reformulating gasoline reduces both regulated and unregulated emissions. As part of a comprehensive policy to reduce vehicle emissions, fuel reformulation could not only offset any increased risks associated with introducing unleaded gasoline, but would complement the elimination of lead health risks. This would result in an overall reduction of the toxic and ozone-forming potential of gasoline, and gasoline vehicle emissions.

The potential for reformulating gasoline to reduce pollutant emissions attracted considerable

Box 2.3: Colorado's Success Story

The success of one program in Colorado (United States) led the U.S. Congress to mandate the use of oxygenated fuels (minimum 2.7 percent oxygen by weight) in areas with serious wintertime CO problems. Colorado initiated a program to require the addition of oxygenates to gasoline during winter months when high ambient CO tends to occur. The mandatory oxygen requirement for the winter of 1988 (January–March) was 1.5 percent by weight, equivalent to about 8 percent MTBE. For the following years, the minimum oxygen content required was 2 percent by weight (equivalent to 11 percent MTBE). These oxygen requirements were estimated to reduce CO exhaust emissions by 24–34 percent in vehicles already fitted with 3-way catalyst systems.

**Box 2.4: The Effects of Oxygenated Gasoline: Wisconsin, Maine, and the U.S.
Environmental Protection Agency**

Wisconsin

- Ambient air monitoring in Milwaukee detected reformulated gasoline components.
- Levels found were not unusually high and did not exceed any health guidelines.
- As in other studies, refueling a vehicle at a station without stage II vapor recovery equipment resulted in the highest exposure potential.
- Symptom prevalence in Milwaukee differed significantly from both Chicago, Illinois, and the remainder of Wisconsin.
- In Milwaukee, people were more likely to report unusual symptoms if they had had a cold or influenza, smoked cigarettes, or were aware of purchasing RFG since November 1994.
- Symptom prevalence in Chicago (an area required to use RFG) was no different from that in greater Wisconsin (an area not required to use RFG).
- This finding suggests that factors other than RFG use significantly contributed to differences in symptom prevalence between Milwaukee and the other two areas studied.
- Individual symptoms and symptom patterns attributed to exposure to reformulated gasoline are non-specific, and similar to those experienced with common acute and chronic illnesses, such as colds, influenza, and allergies.
- Since every symptom was statistically more prevalent in Milwaukee than the other two areas (including symptoms not associated with gasoline or chemical solvent exposure), it suggests that other factors, in addition to the introduction of RFG in that city, contributed to the survey responses.

Respiratory Factors

- All three sample areas experienced the same rate of winter colds and influenza during the 1994–95 season (55–60 percent).
- Having had a cold or influenza was the strongest predictor of unusual symptoms attributed to gaso-

line use among the Milwaukee respondents, but was not a predictor for such symptoms in Chicago or greater Wisconsin.

- The most plausible explanation for this finding is that many symptoms reported by Milwaukee residents may have actually been due to colds or influenza and not RFG exposure; and therefore, other factors (e.g., viruses) may have influenced these adverse health effects.

Awareness of Reformulated Fuels

- Individuals in Milwaukee and greater Wisconsin who purchased RFG since November 1994 were more likely to report specific symptoms than individuals who had not purchased RFG since that date or were not aware of the type of gasoline they purchased.
- Since all gasoline purchased in Milwaukee was RFG, this suggests that knowledge of RFG, including possible awareness of potential negative effects of reformulated gasoline in Milwaukee and greater Wisconsin, may have heightened the perception of current health status and led to the assumption that any health symptoms experienced were unusual and attributable to gasoline exposure.
- This finding is consistent with those in chamber tests where individuals noted RFG had a different odor than traditional gasoline.

Maine

- Complaints reported in January–February 1995. Typical symptoms reported were non-specific dizziness, lightheadedness, and respiratory symptoms.
- After an organized effort to ban the use of RFG was initiated, the Maine Bureau of Health began receiving unsolicited health surveys from York County, Maine. These health surveys were distributed by an organization called “Oxy Busters.” Subsequently, the Bureau of Health received 48 surveys reporting complaints linked to RFG, including odors, headaches, breathing problems, sneezing, and other concerns. These surveys were tabulated and analyzed.

attention in the United States, as pressure to shift to alternative fuels increased during the middle and late 1980s. This effort led to a major cooperative research program between the oil and automobile industries. A similar effort in Europe followed during the early 1990s. Consequently,

a great deal has been learned about the potential to modify gasolines to significantly improve air quality. An additional advantage of fuel reformulation is that it can reduce emissions from all vehicles on the road, much as reducing lead in gasoline reduces lead emissions from all vehicles.

- In response to published newspaper reports, the Bureau of Health also received several letters and numerous telephone calls describing health problems. To date, the vast majority of complaints have originated in York County.
 - This report was written to provide not only an overview and evaluation of specific health concerns that have been linked to RFG, but also to place those concerns specifically in context of Maine. To accomplish this, the health effects of gasoline without 11 percent MTBE, and the health effects of other air toxins in Maine and the nation were weighed.
 - In addition, the introduction of MTBE RFG, during the late fall and early winter, occurred when exposure to other factors having adverse health impacts (influenza and cold viruses, indoor air toxins, severe cold, and dry air) would be maximized.
 - Headaches, skin irritation, and respiratory problems such as sneezing and shortness of breath all increased during this season.
 - The health problems attributed to RFG are very similar to those raised by citizens in other parts of the United States.
 - The investigation of health effects in Alaska appears to be inconclusive and has not been confirmed by similar studies done in New Jersey and New York.
 - The presence of MTBE in groundwater was raised as a significant environmental health and contamination issue by persons questioning the use of MTBE RFG in Maine.
 - Review of the available literature, evaluation of in-state sources of information, and discussions with other states, particularly Colorado, confirms the fact that MTBE has been found in groundwater in Maine and elsewhere in the United States (see the USEPA study).
 - MTBE has been detected in Maine groundwater (and occasionally in drinking water) for about a decade, at levels exceeding the current health-based standard of 50 parts per billion. At present, MTBE in drinking water is not thought to pose a significant health hazard.
 - Furthermore, contamination levels should be decreasing as a problem with leaking underground storage tanks is addressed.
 - Because people have suggested the presently unsubstantiated possibility of significant airborne MTBE contamination of groundwater, increased surveillance for MTBE in groundwater is recommended.
 - The Health Effects Task Force identified a sufficient quantity of available high-quality research information to recommend against banning MTBE RFG because both regular gasoline and ozone represent significant public health hazards and environmental risks.
 - In fact, the use of MTBE RFG, in combination with Stage II vapor recovery mechanisms at service stations, could be expected to achieve some positive health impacts. Significant NO_x reductions are required in RFG Stage II beginning in the year 2000. MTBE health effects have been reviewed by the National Academy of Science and Health Effects Institute in 1996, with generally similar findings.
- The U.S. Environmental Protection Agency**
- Gasoline vapors and vehicle exhaust contain volatile organic compounds (VOCs) and nitrogen oxides (NO_x) that react in the atmosphere in the presence of sunlight and heat to produce ozone, a major component of smog.
 - Motor vehicles also release toxic emissions, including benzene, a known human carcinogen. RFG contains less ingredients contributing to these harmful forms of air pollution. Consequently, RFG reduces the U.S. public's exposure to ozone and certain air toxins.
 - RFG contains oxygen additives (oxygenates) such as MTBE and ethanol. Although used in some fuels as octane enhancers since the late 1970s, oxygenates were first widely used in a oxygenated fuel program begun in 1992 in 39 urban areas.
 - This program was required by the 1990 Clean Air Act in cities with high CO pollution.
 - Oxygenates increase the combustion efficiency of gasoline, thereby reducing motor vehicle CO emissions. CO can also affect healthy individuals by impairing physical capacity, visual perception, manual dexterity, learning functions, and ability to perform complex tasks.
 - To date, research suggests that **the oxygenates used in reformulated gasoline pose no greater a health risk than the standard gasoline RFG replaces**, while helping decrease vehicle emissions. Studies are ongoing, however.

The most significant potential emissions reductions that have been identified for gasoline reformulation have been achieved by making the following changes:

- reducing volatility (to reduce evaporative emissions);
- reducing sulfur (to improve catalyst efficiency); and
- adding oxygenated blend stocks (with a corresponding reduction in the high-octane aromatic hydrocarbons which might otherwise be required).

Lowering volatility: potential benefits of improving various fuel parameters. Fuel volatility, as measured by Reid vapor pressure (RVP), has a marked effect on evaporative emissions from gasoline vehicles with and without evaporative emissions controls. Tests on vehicles without evaporative emissions controls showed that increasing the fuel RVP from 9 pounds per square inch (psi) (62 kilopascals) to approximately 12 psi (82 kPa) roughly doubled evaporative emissions.¹⁸

The effect is even greater in evaporation-controlled vehicles. When fuel RVP was increased from 9 psi (62 kPa) to 12 psi (81 kPa) RVP fuel, USEPA found average diurnal emissions in vehicles with evaporative controls to increase more than 5 times. Also, the average hot-soak emissions increased by 25–100 percent.¹⁹ The large increase in diurnal emissions from controlled vehicles is due to saturation of the charcoal canister, which allows subsequent vapors to escape into the air.

Vehicle refueling emissions are also strongly affected by fuel volatility. In a comparative test on the same vehicle, fuel with 11.5 psi (79 kPa) RVP produced 30 percent greater refueling emissions than gasoline with 10 psi (64 kPa) RVP (1.45 versus 1.89 grams per liter dispensed).²⁰ In response to data such as these, USEPA established nationwide summertime RVP limits for gasoline.

An important advantage of gasoline volatility controls is that they can affect emissions from vehicles already in use, and from the gasoline distribution system. Unlike new-vehicle emissions standards, it is not necessary to wait for the motor vehicle fleet to turn over before they take effect. The emissions benefits and cost-effectiveness of lower volatility are greatest where a few of the vehicles in use are equipped with evaporative controls. Even when evaporative controls are commonly used, as in the United States, controlling volatility may still be beneficial to prevent in-use volatility levels from exceeding those for which controls were designed.

In 1987, USEPA estimated that the long-term refining costs of meeting a 9 psi (62 kPa) RVP limit throughout the United States would be ap-

proximately US\$0.0038 per liter, assuming crude oil at US\$20 per barrel. These costs were largely offset by credits for improved fuel economy and reduced fuel loss through evaporation, leaving a lower net cost to the consumer of approximately US\$0.0012 per liter.

Oxygenates. Blending small percentages of oxygenated compounds such as ethanol, methanol, tertiary butyl alcohol, and MTBE with gasoline reduces the fuel's volumetric energy content, while improving antiknock performance. Oxygenates thus make possible a potential reduction in lead and harmful aromatic compounds. Assuming no change in the settings of the fuel metering system, adding oxygenates will result in a leaner air-fuel mixture, which will reduce exhaust CO and HC emissions. These reductions are becoming less and less important due to recent models that do not overfuel the engine, and better adaptive learning fuel management systems.

Other fuel variables: Sulfur. Lowering sulfur in gasoline lowers CO, HC, and NO_x emissions from catalytic converter-equipped cars. As noted by the *Auto/Oil* study, "The regression analysis showed that the sulfur effect (lowered emissions) was significant for HC on all ten cars, CO on five cars, and NO_x on eight cars. There were no instances of a statistically significant increase in emissions."²¹ To the extent that oxygenates are sulfur-free, their addition would tend to lower gasoline sulfur levels. The study indicated that NO_x would go down by about 3 percent per 100 ppm sulfur reduction. Recently, the Canadian Government has determined that sulfur causes atmospheric formation of fine particles and that sulfur reduction would yield 90 percent of the health benefits expected from its proposed reformulations.

Other fuel variables. Results of the *Auto/Oil* study demonstrated that "NO_x emissions were lowered by reducing olefins, raised when T₉₀ was reduced; and only marginally increased when aromatics were lowered."²² In general, reducing

aromatics and T_{90} caused statistically significant reductions in exhaust mass NMHC and CO emissions. Reducing olefins increases exhaust mass NMHC emissions. However, "the ozone forming potential" of the total vehicle emissions was reduced.²³

Regarding toxins, the reduction of aromatics from 45 percent to 20 percent caused the following:

1. 42 percent reduction in benzene but a 23 percent increase in formaldehyde,
2. 20 percent increase in acetaldehyde and about a 10 percent increase in 1,3-Butadiene, and
3. 31 percent reduction in 1,3-Butadiene, but insignificant impacts on other toxins.

Reducing olefins from 20 percent to 5 percent resulted in a 31 percent reduction in 1,3-Butadiene but had an insignificant impact on other toxics. Lowering the T_{90} from 360°F to 280°F resulted in statistically significant reductions in benzene, 1,3-Butadiene (37 percent), formaldehyde (27 percent), and acetaldehyde (23 percent).

Cost-effectiveness. It is difficult to estimate the costs and cost-effectiveness of fuel modification, because fuels' characteristics differ widely from one refiner to another. Individual fuel component control costs, and the effects of changes in one fuel component versus another are two integral parts in determining cost effectiveness. USEPA studied these two integral parts: results derived from refinery modeling performed by Turner, Mason, and Company (for the *Auto-Oil Economics* group) and Bonner & Moore Management Science (for USEPA). Survey results

Box 2.5: Impact of Oxygenate Used

MTBE: Can be added to gasoline up to 2.7 percent without any significant increase in NO_x . Two opposing effects appear to take place with addition of oxygenates.

1. Enleanment, which tends to raise NO_x .
2. Lower flame temperatures, which tend to reduce NO_x .

With MTBE levels below the equivalent of 2.7 percent oxygen, the lower flame temperature effect seems to prevail.

Ethanol: Can be added to gasoline at levels as high as 2.1 percent oxygen without significantly increasing NO_x levels; above that point levels could increase (e.g., USEPA test data on over 100 cars indicates that oxygen levels of 2.7 percent or more could increase NO_x emissions by 3–4 percent). The *Auto Oil Air Quality Improvement Research Program (Auto/Oil)* concluded that there was a statistically significant increase (of about 5 percent) in NO_x with the addition of 10 percent ethanol (3.5 percent oxygen).

ETBE: Appears to be an attractive source of oxygenates. However, not enough data exists regarding its NO_x impact to come to a reasonable conclusion about it. The *Auto/Oil* study revealed an approximately 6 percent increase in NO_x , but the results were not statistically significant.

presented by the California Air Resources Board (CARB) were also figured into the study.

The total manufacturing cost of producing reformulated gasoline is the sum of the capital recovery cost and the operating cost. An example of the individual fuel component costs and the associated incremental percent reduction in VOC emissions is shown in table 2.4.

USEPA proposed a range of VOC standards and NO_x standards based on particular combinations of fuel component controls which reduce VOC (and VOC plus NO_x) emissions at a cost of less than US\$5,000 and less than US\$10,000 per ton, respectively. USEPA believes these ranges to represent the upper limit of costs that will be incurred by many ozone non-attainment areas while achieving attainment.

Estimates of the costs and cost effectiveness of California RFG continue to come down. While developing regulations, CARB estimated costs to be US\$0.12–0.17 per gallon. Recently, a USEPA analysis placed the costs at US\$0.08–0.11 per gallon (US\$0.02–0.03 per liter). This analysis estimated the cost effective-

ness of the California RFG to be US\$4,100–5,100 per ton of VOC and NO_x control; Federal Phase 1 RFG was estimated to cost US\$3,100 per ton of VOC control.²⁴

LUBRICANTS FOR TWO-STROKE ENGINES

There is a visible “blue” or white smoke in the exhaust of a two-stroke engine, due to the all-loss system of lubrication. This is further exacerbated by ex-

cessive use of lubrication, especially if the lubricant or gasoline is adulterated, or used in a poorly-maintained engine. The use of modern synthetic smokeless lubricants is recommended for two-stroke engines (especially three-wheelers) in urban areas. The environmental benefits far outweigh the small extra cost. A government requirement mandating the dispensing of quality lubricants, along with gasoline at authorized dealers for the two-stroke vehicles, would deter adulteration of gasoline and lubricating oils.

CONCLUSIONS REGARDING CLEANER GASOLINE

1. A growing body of data on lead’s adverse health effects, especially in young children, indicates there may be no “safe” level. Reduced lead in gasoline has been shown to reduce the risk of behavioral problems, lowered IQs, and decreased ability to concentrate. Adult health is also affected by blood lead which increases the risk of high blood pressure and cardiovascular diseases.

Table 2.4: Component Control Costs and VOC Emissions Reductions

Component	Control Level (c/gal)	Incremental Cost	Cumulative VOC Reduction (%)
Oxygen	2.0 Wt %	1.67-3.36 *	9.0
Benzene	1.0 vol %	0.69	9.0
RVP	8.1 psi	0.57	17.6
RVP	7.4 psi	1.67	25.3
Sulfur	160 ppm	0.35-0.57	26.4
Oxygen	2.7 Wt %	0.59-1.18 *	
Olefins	5.0 vol %	1.81-2.44	30.2
Sulfur	50 ppm	1.45-1.86	31.2
Aromatics	20%	0.61-0.98	31.4

* Based on MTBE.

2. Lead scavengers that accompany leaded gasoline have been identified as human carcinogens; eliminating lead in gasoline will reduce this cancer risk.
3. Studies in both Europe and the United States show that gasoline lead is responsible for about 90 percent of airborne lead and that 1 microgram per cubic meter of ambient lead will cause a 1–2 microgram per milliliter increase in blood lead levels. This is in addition to the lead burden which may be associated with food, drinking water, and other sources; this burden can vary dramatically from country to country.
4. The availability of lead-free gasoline can facilitate extensive reductions in other major motor vehicle pollutants, hydrocarbons, CO, NO_x, aldehydes, and polynuclear aromatic hydrocarbons (PAHs), by allowing the use of catalytic converters.
5. Motor vehicle emissions of HC, CO, and NO_x cause or contribute to a wide range of adverse impacts on public health and general well-being. Those impacts include increased angina attacks in individuals suffering from angina pectoris, greater susceptibility to respiratory

infection, more respiratory problems in school children, increased airway resistance in asthmatics, eye irritation, impaired crop growth, dead lakes, and forest destruction. Emissions reductions can occur simultaneously with equally significant reductions in fuel consumption and vehicle maintenance. Studies in Canada support reduced maintenance costs, as a result of using unleaded gasoline, of about Can\$0.024 per liter.

6. The best strategy for eliminating lead in gasoline is to eliminate its use over a specific time period, as several countries have done.
7. Tax policies that price unleaded fuel substantially lower than leaded fuel have been found to be very effective in stimulating the sales of unleaded fuel. Hong Kong and Singapore have adopted such policies.
8. Countries concerned about limited supplies of unleaded gasoline may wish to maintain a higher price for unleaded gasoline. This strategy, however, tends to favor the continued purchase of cheaper leaded fuel, increasing the risk of damaging the catalytic converter.
9. Reformulating gasoline by modifying parameters such as volatility, oxygenates, sulfur levels, and HC mix can reduce HC, CO, and toxic emissions by 10–30 percent.
10. Using oxygenates such as MTBE in cold temperature environments clearly reduces CO, but has raised concerns regarding adverse health effects in certain susceptible individuals. Studies to date by USEPA and several U.S. states have failed to identify a serious problem, but additional studies are ongoing.
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CHAPTER 3: DIESEL FUEL

The quality and composition of diesel fuel can have important impacts on pollutant emissions. Diesel-powered vehicles are an important part of commercial vehicle fleets throughout the world. They also produce large amounts of particulate matter emissions from unburned fuel and lubricating oil, and from sulfur in the fuel. Diesel particulate emissions are very small and thus have a maximum health impact. Because diesel combustion produces very high flame temperatures, high amounts of nitrogen oxides (NO_x) are produced. NO_x contributes to photochemical smog and, through secondary atmospheric transformations, to particulate aerosols. Improved engine designs and, very recently, add-on devices such as oxidation catalysts or particulate filters have achieved considerable success in reducing particulate matter emissions. Traps that rely on fuel additive catalysts such as cerium for semi-continuous regeneration have also been successful in reducing emissions. However, even with these advances, cleaner diesel vehicle particulate emissions remain much higher than from comparable gasoline-fueled vehicles. (For a review of controls on diesel-fueled vehicles, see appendix C.)

Box 3.1: Fuel Variables Found to Have a Significant Impact on Pollutant Emissions

1. Sulfur content and the fraction of aromatic hydrocarbons contained in the fuel.
2. Volatility of the diesel fuel (85 or 90 percent distilled temperatures).
3. Use of fuel additives.

SULFUR

Diesel emissions contain sulfur in particulate and gaseous form, and thus any reduction in sulfur has dual advantages. Recent evaluations carried out in Europe show the benefits of reduced sulfur in diesel fuel for lowering particulates. For example, preliminary data released from the *Auto/Oil* study showed that lowering the diesel fuel sulfur level from 2000 particles per million (ppm) to 500 ppm reduced overall particulate from light-duty diesels by 2.4 percent, and from heavy-duty diesels by 13 percent.¹ The relationship between particulates and sulfur level was found to be linear; for every 100 ppm reduction in sulfur, there is a 0.16 percent reduction in particulate from light-duty vehicles and a 0.87 percent reduction from heavy-duty vehicles.

USEPA has also established a clear relationship between sulfur in diesel fuel and particulate emissions.² The direct sulfate emissions factor (grams per mile) is calculated as follows:

$$\text{DSULV} = 13.6 * (1.0 + \text{WATER}) * \text{FDNSTY} * \text{SWGHTD} * \text{DCNVRT}/\text{FE}$$

DSULV: direct sulfate emissions factor for a class and model year of vehicles.

DCNVRT: fraction of sulfur in the fuel that is converted directly to sulfate (2.0 percent).

FDNSTY: density of diesel fuel (7.11 pounds per gallon).

FE: fuel economy for the class and model year of the vehicles.

SWGHTD: weight percent of sulfur in diesel fuel.

WATER: weight ratio of seven water molecules to sulfate, $7 * 18/96 = 1.31$.

13.6: units conversion factor = $(453.59 * 3)/100$
 where 453.59 = number of grams in a pound,
 3 = weight ratio of SO₄ to sulfur, and the division by 100 is to correct for the weight percent of sulfur.

The gaseous sulfur emissions factor is calculated as follows:

$$SO_{2EF} = 9.07 * FDNSTY * SWGHTD * (1 - CNVRT)/FE$$

SO_{2EF} = the sulfur emissions factor of a vehicle of a given class and model year.

9.07: units conversion factor = $(453.59 * 2)/100$
 where 453.59 = number of grams in a pound,
 2 = weight ratio of SO₂ to sulfur, and the division by 100 is to convert for the weight percent of sulfur.

Clearly, improving diesel fuel quality reduces diesel emissions and increases the prospects for advanced after-treatment technology. Sweden and Finland have shown that very low-sulfur diesel fuel is feasible and beneficial. Both countries have introduced the use of very low-sulfur fuel (less than 0.005 percent by weight), resulting in substantially reduced sulfur emissions.

Sweden introduced environmental classifications for diesel fuel in January 1991, with tax relief for both sulfur content and composition. These were further revised in January 1992 to the classifications summarized in table 3.1. Figure 3.1 illustrates the benefits produced by using very low-sulfur diesel fuel on urban buses in Finland.³

Certain precious metal catalysts can oxidize SO₂ to sulfur trioxide (SO₃), which combines with water in the exhaust to form sulfuric acid. The rate of conversion with the catalyst depends on the temperature, space velocity, and oxygen content of the exhaust, and on the activity of the catalyst. Generally, catalyst formulations that are most effective in oxidizing hydrocarbons and CO are also most effective at oxidizing SO₂. The presence of significant quantities of sulfur in diesel fuel thus limits the potential for emissions catalysts or catalytic trap-oxidizers for use in controlling PM and HC emissions.

Atmospheric SO₂ oxidizes to form sulfate particles much the way it does in the precious metal catalyst. The presence of the catalyst merely speeds up a reaction which would occur anyway (although this can have a significant effect on human expo-

Table 3.1: Environmental Classifications for Sweden

Fuel Characteristic	Urban Diesel 1	Urban Diesel 2	Standard
Maximum Sulfur (%)	0.001	0.005	0.2
Maximum Aromatics (%)	5	20	-
Maximum PAH (%)	0.02	0.1	-
Distillation:			
IBP (min) 0 C	180	180	-
10 percent (min)	-	-	180
95 percent (max)	285	295	*
Density (kg/m ³)	800-820	800-820	#
Cetane Number	50	47	##
Tax Rate (\$/m ³)@	126	165	199

Notes:

In addition to the urban grades, one summer and three winter standard grades are specified.

* 95 percent distillation varies with grade: Summer 370; Winter 340

Density varies with grade: Summer 820-860 kg/m³; Winter 800-845 (-26 C); Winter 800-840 (-32 and -38 C grades)

45-49

@ 1994 tax rates exclude added value tax.

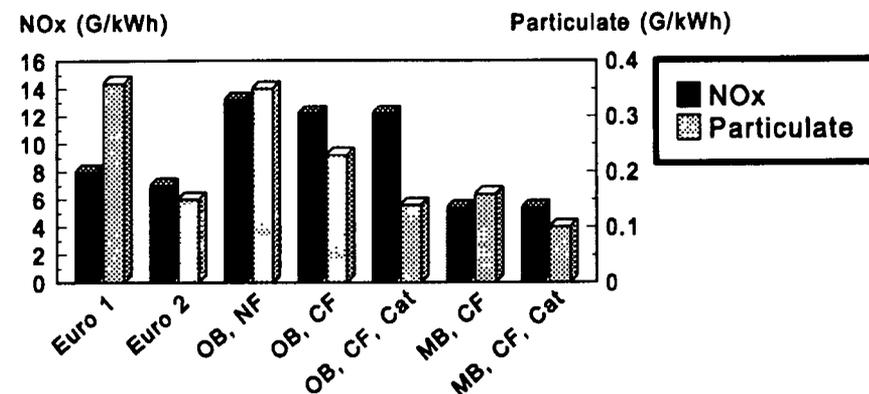
sure to reaction products). According to analysis by California Air Resources Board staff, roughly 1.2 pounds of secondary particulate is formed per pound of SO_2 emitted in the South Coast Air Basin. For a diesel engine burning fuel of 0.29 percent by weight of sulfur at 0.42 pounds of fuel per horsepower per hour, this is equivalent to 0.85 grams per horsepower-hour. For comparison, the average rate of primary or directly emitted particulate emissions from heavy-duty diesel engines in use was about 0.8 grams per horsepower-hour.

Aside from its particulate-forming tendencies, SO_2 is recognized as a hazardous pollutant in its own right. The health and welfare effects of SO_2 in diesel vehicle emissions are probably much greater than that of an equal quantity emitted from a utility stack or industrial boiler, since motor vehicle exhaust is emitted close to ground level near roads, buildings, and people.

VOLATILITY

Diesel fuel consists of a mixture of hydrocarbons having different molecular weights and boiling points.⁴ As a result, some of it boils away on heating, while the remainder's boiling point increases. This fact is used to characterize the range of hydrocarbons in the fuel in the form of a "distil-

Figure 3.1: Emissions from Buses in Finland



Note: OB = Old Bus; MB = Modern Bus; NF = Normal Fuel; CF = City Diesel; CAT = Oxidation Catalysts

lation curve," specifying the temperature at which various percentages of the hydrocarbons have boiled away. A low (10 percent) boiling point (T_{10}) is associated with a significant content of relatively volatile hydrocarbons. Fuels with this characteristic tend to exhibit somewhat higher HC emissions than others. Formerly, a relatively high (90 percent) boiling point (T_{90}) was considered to be associated with higher particulate emissions. More recent European studies have shown that this effect is spurious—the apparent statistical linkage was due to the higher sulfur content of these high-boiling fuels.

In a Dutch study, the test fuels were composed of two sets of clearly different (T_{85} and T_{90}) boil-

Box 3.2: Options to Reduce the Sulfur Content of Diesel Fuel

1. In the crude state, increase the proportion of low-sulfur crude oil.
2. Reduce the cut point of diesel fractions from both primary distillation as well as from the fractionation of secondary processing streams to 350–360°C.
3. Improve fractionation efficiency to eliminate inter-stream overlaps during fractionation of diesel oils.
4. Hydro-treat gas oil feedstocks to fluid catalytic cracking (FCC) and/or hydrofine FCC diesel fractions; reduce proportions of FCC oil blended into final product diesel oil to reduce olefins and avoid stability problems.
5. Install hydrocrackers that would enable production of very low-sulfur saturated diesel with high cetane numbers.

ing points, between which sulfur content varied independently. A highly significant effect of 85–90 percent boiling point temperatures was found, in addition to a significant sulfur effect and a probably significant aromatics content effect. A typical effect of a 20°C change in 85 percent boiling point is 0.05 grams per kWh at present particulate levels. As mentioned earlier, this may be related to generally higher 85 or 90 percent boiling points, which in the test fuels went up to 350–360°C. Commercial diesel fuels in Europe show values up to about 370°C.

AROMATIC HYDROCARBON CONTENT

Aromatic hydrocarbons are compounds containing one or more benzene-like ring structures. They are distinguished from paraffins and naphthenes, the other major hydrocarbon constituents of diesel fuel, which lack such structures. Aromatic hydrocarbons are denser, have poorer self-ignition qualities, and produce more soot in burning. Ordinarily, “straight run” diesel fuel produced by simple distillation of crude oil is fairly low in aromatic hydrocarbons. However, catalytic cracking of residual oil to increase gasoline and diesel production results in increased aromatics content. A typical straight run diesel might contain 20–25 percent aromatics by volume, while a diesel blended from catalytically cracked stocks could have 40–50 percent aromatics.

Aromatic hydrocarbons have poor self-ignition qualities, so diesel fuels containing a high fraction of aromatics tend to have low cetane numbers. Typical cetane values for straight run diesels are in the range of 50–55; those for highly aromatic diesel fuels are typically 40–45, and may be even lower. This produces delays in starting vehicles when the engine is cold, and increases combustion noise, HC, and NO_x .

Increased aromatics content is also correlated with higher particulate emissions. Aromatic hydrocarbons have a greater tendency to form soot while burning, and the poorer combustion quality also appears to increase particulate soluble

organic fraction (SOF) emissions. Increased aromatic content may also be correlated with increased SOF mutagenicity, possibly due to increased polycyclic nuclear aromatics (PNA) and nitro-PNA emissions. There is also some evidence that more highly aromatic fuels have a greater tendency to form deposits on fuel injectors and other critical components. Such deposits can interfere with proper fuel/air mixing, greatly increasing PM and HC emissions.

OTHER FUEL PROPERTIES

Other fuel properties may also have an effect on emissions. Fuel density, for instance, may affect the mass of fuel injected into the combustion chamber, and thus the air/fuel ratio. This is because fuel injection pumps meter fuel by volume, not by mass, and a denser fuel contains a greater mass in the same volume. Fuel viscosity can also affect the fuel injection characteristics, and thus the mixing rate. The fuel’s corrosiveness, cleanliness, and lubricating properties can all affect the fuel injection equipment—possibly contributing to excessive in-use emissions if the equipment wears out prematurely. Reducing fuel density is an effective means of reducing fine particulate emissions.

FUEL ADDITIVES

Several generic types of diesel fuel additives, including cetane enhancers, smoke suppressants, and detergent additives, can also have a significant impact on emissions. In recent years some additive research has been directed specifically at emissions reduction.

Cetane enhancers are used to improve diesel fuel’s self-ignition qualities. These compounds are generally added to reduce combustion noise and ignition delays, both adverse impacts of high aromatic fuels. Cetane enhancers also appear to reduce the aromatic hydrocarbons’ adverse impacts on HC and PM emissions. However, PM

emissions are somewhat higher than what would result from the use of a higher quality fuel. These findings are not universal. A Dutch study detected no significant effect of ashless cetane-enhancers on NO_x or particulates.

Smoke-suppressing additives are organic compounds of calcium, barium, or sometimes magnesium. Added to diesel fuel, these compounds inhibit soot formation during the combustion process, and thus greatly reduce visible smoke emissions. Their effects on the particulate SOF are not fully documented, but one study of a barium additive has shown a significant increase in the polynuclear aromatic hydrocarbons (PAH) content and SOF mutagenicity.

Particulate sulfate emissions are greatly increased with these additives, since they readily form stable solid metal sulfates which are emitted in the exhaust. Thus, the overall effect of reducing soot and increasing metal sulfate emissions may be either an increase or decrease in the total particulate mass, depending on the soot emissions level at the beginning, and the amount of additive used.

Detergent additives (often combined with a cetane enhancer) help to prevent and remove coke deposits on fuel injector tips and other vulnerable locations. By maintaining new engine injection and mixing characteristics, these deposits can help to decrease in-use PM and HC emissions. A study for the California Air Resources Board (CARB) estimated that fuel injector problems of trucks in use cause PM emissions that are 50 percent higher than those from new vehicles. A significant fraction of this PM emissions excess is unquestionably due to fuel injector deposits.

CONCLUSIONS REGARDING CLEAN DIESEL FUEL

1. There is a clear worldwide trend toward lower levels of sulfur in diesel fuel. At a minimum, this would reduce particulate emissions from diesel vehicles. Recent European studies indicate that for every 100 ppm sulfur reduction, there is a 0.16 percent reduction in particulates from light-duty vehicles, and a 0.87 percent reduction from heavy-duty vehicles.
2. Other diesel fuel properties such as volatility, density, aromatic content, and additives can have positive or negative effects on diesel vehicle emissions. Increasing the cetane number of the fuel usually has beneficial effects on emissions.
3. In addition to the adoption of mandatory limits, studies show that tax policies can be very effective in encouraging the introduction and use of low-polluting diesel fuels.

ENDNOTES

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4. Boiling points are measured in terms of units of temperature (T), the temperature at which gasoline is vaporized or distilled.

CHAPTER 4: ALTERNATIVE FUELS

The possibility of substituting cleaner-burning alternatives for gasoline has drawn increasing attention over the last decade. Motives for these substitutions include conservation of oil products and energy security, as well as reducing or eliminating pollutant emissions. Some alternative fuels offer large, cost-effective reductions in pollutant emissions. Alternative fuels' air quality claims must be evaluated carefully, because in many cases similar or even greater emissions reductions can be obtained with a conventional fuel by using a more advanced emissions control system. Which approach is more cost-effective depends on the relative costs of the conventional and the alternative fuel.¹

Alternative fuels include the following:

- methanol (derived from natural gas, coal, or biomass);

- ethanol (derived from grain);
- biodiesel (derived from vegetable or other oils);
- compressed natural gas (CNG, mainly composed of methane);
- liquefied petroleum gas (LPG, composed of propane and butane);
- electricity;
- hydrogen; and
- synthetic liquid fuels derived from hydrogenation of coal, and various fuel blends such as gasohol.

NATURAL GAS

Natural gas (85–99 percent methane) has many desirable qualities as a spark-ignition engine fuel. Clean-burning, cheap, and abundant in many

Table 4.1: Properties of Conventional and Alternative Fuels

Fuel Type	Diesel	Gasoline	Methanol	Ethanol	Propane	Methane
Energy content (LHV) (MJ/kg)	42.5	44.0	20.0	26.9	46.4	50.0
Liquid density (kg/l)	0.84-0.88	0.72-0.78	.792	.785	.51	.4225
Liquid energy density (MJ/l)	36.55	33.0	15.84	21.12	23.66	21.13
Gas energy density (MJ/l)						
- @ atmospheric	--	--	--	--	0.093	0.036
- @ 200 bar	--	--	--	--	--	7.47
Boiling point, 0C	140-360	37-205	65	79	-42.15	-161.6
Research octane no.	~25	92-98	106	107	112	120
Motor octane no.	--	80-90	92	89	97	120
Cetane no.	45-55	0-5	5	5	~2	0

parts of the world, natural gas already plays a significant role in Argentina, Canada, Italy, New Zealand, Russia, and the United States. Recent advances in natural gas vehicle and engine technology in a number of countries have combined to boost natural gas' visibility and market potential as a vehicle fuel. Other advances include new storage cylinder technologies, international standardization, and new factory-manufactured natural gas vehicles (NGVs). These have helped enhance the market potential of natural gas.

Nearly all NGVs now in operation have been retrofitted from gasoline models. Natural gas' physical properties make these conversions relatively easy. A typical conversion costs about US\$1,500–4,000 per vehicle, due mostly to the on-board fuel storage system's cost. Current fuel prices mean that many high-use vehicles could recover this cost in a few years due to fuel cost savings.

In recent years, several thousand new, factory-built light-duty NGVs have been produced in the United States, mostly by the Chrysler Corporation. Ford has announced plans to begin limited production of an optimized natural gas passenger car in 1996. The Chrysler and Ford vehicles incorporate fuel metering and emissions control systems similar to those in modern fuel-injected gasoline vehicles. These vehicles are the cleanest non-electric motor vehicles ever made—easily meeting California's stringent ultra-low vehicle emissions standards. Their incremental cost in their present, limited-volume production, range about US\$4,000–5,500 more than gasoline vehicles, or about 20 percent of the selling price. Estimates claim that under mass production the incremental cost would drop to around US\$1,500–2,500 per vehicle.

Natural gas engines can be grouped into three main types by combustion system—stoichiometric, lean-burn, and dual-fuel diesel.

Most NGVs now in operation have **stoichiometric engines** that have been converted from gasoline engines. These engines are either bi-fuel (able to operate on natural gas or gasoline) or dedicated to natural gas. In the latter case, the engine can be optimized for natural gas by in-

creasing the compression ratio and making other changes, although this is not usually done in retrofitting situations because of the cost. Nearly all present light-duty NGVs use stoichiometric engines with or without three-way emissions catalysts. A few heavy-duty natural gas vehicles also use stoichiometric engines.

Lean-burn engines use an air-fuel mixture with significantly more air than is required to burn all of the fuel. The extra air dilutes the mixture and reduces the flame temperature, reducing engine-out nitrogen oxide (NO_x) emissions and exhaust temperatures. Reduced heat losses and various thermodynamic advantages make lean-burn engines approximately 10–20 percent more efficient than stoichiometric engines. Without turbocharging, however, a lean-burn engine's power output is less than that of a stoichiometric engine. Turbocharging reverses the situation because lean mixtures knock less readily. Therefore, lean-burn engines can be designed for higher levels of turbocharger boost than stoichiometric engines, thus achieving higher power output. These engines' lower temperatures also contribute to engine life and reliability. For these reasons, most heavy-duty natural gas engines have a lean-burn design. This category includes a rapidly-growing number of heavy-duty lean-burn engines developed and marketed specifically for vehicular use.

Dual-fuel diesel engines are a special type of lean-burn engine in which the air-gas mixture in the cylinder is ignited not by a spark plug but by injection of a small amount of diesel fuel that self-ignites. Most diesel engines can readily be converted to dual-fuel operation, retaining the option to run on 100 percent diesel fuel if natural gas is not available. Because of the flexibility this allows, the dual-fuel approach has been popular for heavy-duty retrofit applications. Current dual-fuel engine systems tend to have very high HC and CO emissions due to the production of mixtures too lean to burn at light loads. However, developments such as timed gaseous fuel injection systems, promise to overcome this problem.

Since natural gas is mostly methane, NGVs have lower non-methane hydrocarbon (NMHC) emissions than gasoline vehicles, but higher methane emissions. When the fuel system is sealed, there are no evaporative or running-loss emissions, and refueling emissions are negligible. Cold-start emissions from NGVs are also low since cold-start enrichment is not required, reducing both NMHC and CO emissions. NGVs are normally calibrated with somewhat leaner fuel-air ratios than gasoline vehicles, which also reduces CO emissions. Given equal energy efficiency, carbon dioxide (CO₂) emissions from NGVs are lower than from gasoline vehicles, since natural gas has a lower carbon content per unit of energy. In addition, the high octane value of natural gas (120 or more) makes it possible to attain increased efficiency by increasing the compression ratio. Optimized heavy-duty NGV engines may approach diesel efficiency levels. NO_x emissions from uncontrolled NGVs may be higher or lower than comparable gasoline vehicles, depending on the engine technology, but they are typically somewhat lower. Light-duty NGVs equipped with modern electronic fuel control systems and three-way catalytic converters have achieved NO_x emissions more than 75 percent below the California ultra-low vehicle emissions standards.

In the last several years, a number of heavy-duty engine manufacturers have developed diesel-derived lean-burn natural gas engines for use in emissions-critical applications, such as urban transit buses and delivery trucks. These engines incorporate low-NO_x technology used in stationary natural gas engines, and typically an oxidation catalyst. They are capable of achieving very low NO_x, particulate, and other emissions levels (less than 2.0 grams per BHP-hr NO_x and 0.03 grams per BHP-hr particulate) with high efficiency, high power output, and most likely, longer life. Three such engines have recently been certified in California: the Cummins L10 engine for transit buses, and the Hercules 5.6l and 3.7l engines for school buses and medium trucks.

Natural gas costs vary greatly from country to country, and even within countries, due to in-

frastructure and transport costs. Where gas is available by pipeline from the field, its price is normally set by competition with residual fuel oil or coal. Market-clearing price under these conditions is typically about US\$3.00 per million BTU (equivalent to about \$0.41 per gallon of diesel fuel). Natural gas compression costs can add another US\$0.50–2.00 per million BTU, depending on the facility's size and the natural gas supply pressure.

Liquefied natural gas (LNG) costs vary considerably, depending on specific contract terms (there is no effective "spot" LNG market). Small-scale natural gas liquefaction costs about US\$2.00 per million BTU, normally making it uneconomic compared to CNG. Where low-cost remote gas is available, LNG production can be quite economic. Typical 1987 costs for LNG delivered to Japan were about US\$3.20–3.50 per million BTU. Terminal receipt and transportation would probably add about US\$0.50 to the wholesale cost.

LIQUEFIED PETROLEUM GAS

Liquefied petroleum gas (LPG) is already widely used as a vehicle fuel in Canada, the Netherlands, and the United States. As a spark-ignition engine fuel, it has many of the same advantages as natural gas, with the additional advantage of being easier to transport. A major disadvantage is its limited supply, which would rule out any large-scale conversion to LPG fuel. As with natural gas, nearly all LPG vehicles presently in operation are retrofitted gasoline vehicles. The costs of converting from gasoline to LPG are considerably less than those of converting to natural gas, due primarily to the fuel tanks' lower cost. A light-duty vehicle typically costs about US\$800–1,500 to convert. As with natural gas, the conversion cost for high-use vehicles usually can be recovered within a few years through lower fuel costs. Engine technology for LPG vehicles is very similar to that for NGVs, with the exception that LPG is seldom used in dual-fuel diesel applications.

LPG has many of the same emissions characteristics as natural gas. The two fuels are similar, except that LPG is primarily propane (or a propane/butane mixture), rather than methane, which affects the composition of exhaust volatile organic compound (VOC) emissions. LPG is produced in the extraction of heavier liquids from natural gas, and as a by-product in petroleum refining. Presently, LPG supply exceeds demand in most petroleum-refining countries, which keeps the price low relative to other hydrocarbons. Wholesale prices for consumer-grade propane in the United States have been about US\$0.25–0.30 per gallon for several years, or about 30 percent less than the wholesale cost of diesel on an energy basis. Depending on the location, however, the additional costs of storing and transporting LPG may offset this advantage.

METHANOL

Widely promoted in the United States as a “clean fuel,” methanol has many desirable combustion and emissions characteristics, including good lean-combustion characteristics, low flame temperature (leading to low NO_x emissions), and low photochemical reactivity. Methanol’s major drawbacks are its cost and price volatility. There is little prospect for methanol to become price-competitive with conventional fuels unless world oil prices increase greatly.

With a fairly high octane number of 112 and excellent lean-combustion properties, methanol is a good fuel for lean-burn Otto-cycle engines. Its lean combustion limits are similar to those of natural gas, while its low energy density results in a flame temperature lower than hydrocarbon fuels, and thus lower NO_x emissions.

Light-duty vehicles using M₈₅ tend to have NO_x and CO emissions similar to gasoline vehicles. The total mass of tailpipe non-methane organic gas (NMOG) emissions tends to be similar to (or higher than) gasoline vehicles, but NMOG’s lower ozone reactivity results in simi-

lar or somewhat lower ozone impacts. Formaldehyde emissions (a primary combustion product of methanol) tend to be significantly higher than those from gasoline or other alternative fuel vehicles. However, other toxic air emissions (especially benzene) tend to be lower, while formaldehyde emissions have been controlled successfully by emissions catalysts.

Heavy-duty methanol engines are capable of much lower NO_x and particulate emissions than similar heavy-duty bus diesel engines, while engine-out NMOG and formaldehyde emissions tend to be higher. However, these emissions have been controlled successfully by emissions catalyst converters.

Methanol can be produced from natural gas, coal, or biomass. At current and foreseeable prices, the most economical methanol feedstock is natural gas, especially where found in remote regions where natural gas has no ready market. The current world market considers methanol a commodity chemical, rather than a fuel; world methanol production capacity is limited and projected to be tight through the 1990s and beyond. Methanol is a feedstock in the production of MTBE, and anticipated increased demand for MTBE for reformulated gasoline will place strong pressures on price and supply in the foreseeable future.

The world market price of methanol has fluctuated dramatically in the last decade, from US\$0.25 per gallon in the early 1980s to US\$0.60–0.70 in the late 1980s. The lower price reflected a glut, while the higher value reflected a temporary shortage. Recent estimates of the long-term supply price of methanol for the next decade are US\$0.43–0.59 per gallon. This would be equal to US\$0.90–1.23 on an energy-equivalent basis (compared to present spot gasoline prices on the order of US\$0.70 per gallon). In addition to new methanol supply capacity, any large-scale vehicular use of methanol would require substantial investments in fuel storage, transportation, and dispensing facilities, which would further increase the delivered cost of the fuel.

ETHANOL

Ethanol has attracted considerable attention as a motor fuel due to the success of the Brazilian *Proalcool* program. However, despite this program's technical success, the high cost of producing ethanol (compared to hydrocarbon fuels) means that heavy subsidies are required.

Ethanol, the second lowest of the alcohols in molecular weight, resembles methanol in most combustion and physical properties. The major difference is ethanol's higher volumetric energy content. Fuel-grade ethanol, as produced in Brazil, is produced by distillation, and contains several percent by weight of water. In addition, pure (anhydrous) ethanol is used as a blend stock for gasoline both in Brazil and the United States. By blending 22 percent anhydrous ethanol with gasoline to produce gasohol, Brazil has been able to completely eliminate the need for lead as an octane enhancer.

Emissions from ethanol-fueled engines are not well characterized but are believed to be high in unburned ethanol, acetaldehyde, and other aldehydes. These can be controlled with emissions catalysts. Uncontrolled NO_x emissions are somewhat higher than with methanol, but still lower than gasoline engines. Cold-starting ethanol engines is not a serious problem in the warm Brazilian climate but would be a concern in colder countries.

Ethanol is produced primarily by fermenting starch from grains or sugar (from sugar cane). As a result, fuel ethanol production directly competes with food production in most countries. Ethanol's resulting high price—US\$1.00–1.60 per gallon in the United States in the last few years (equivalent to US\$1.56–2.50 per gallon of gasoline on an energy basis), has effectively ruled out its use as a motor fuel except in Brazil and the United States, where it is heavily subsidized. Brazil's *Proalcool* program, promoting the use of fuel ethanol in motor vehicles, has attracted worldwide attention as the most successful alternative fuel implementation program. Despite the

availability of a large and inexpensive biomass resource, this program still depends on massive government subsidies.

BIODIESEL

Biodiesel is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower-viscosity fuel similar in physical characteristics to diesel. Such fuels can be used as is or blended with diesel. Engines running on pure biodiesel tend to have lower black smoke and CO emissions but higher NO_x emissions, and possibly higher particulate emissions. These differences are not very large. Other advantages of biodiesel include a high cetane number, very low sulfur content, and the fact that it is a renewable resource. Disadvantages include high cost (US\$1.50–3.50 per gallon before taxes), reduced energy density resulting in lower engine power output, and a low flash point, which may be hazardous. Biodiesel's effects on engine performance and emissions over long-term use are not well documented.

Although there are no published field test data on engine emissions or performance and durability for vehicles using blended or neat biodiesel, there are some reports on short-term effects measured in the laboratory. The general consensus is that blended or neat biodiesel has the potential to reduce CO emissions (although these are already low), smoke opacity, and measured HC emissions. However, studies show an increase in NO_x emissions from biodiesel fuel, compared to diesel fuel under normal engine conditions. This is partly due to biodiesel's higher cetane number, which causes a shorter ignition delay and higher peak cylinder pressure (some may also be due to the fuel's nitrogen content). Reduction in smoke emissions is believed to be due to better combustion of the short-chain hydrocarbons found in biodiesel, as well as the oxygen content's effect. Other data also show that mixing oxygenates with biodiesel indicates a reduction in HC emissions when biodiesel is used. However, the

organic acids and oxygenated compounds found in biodiesel may affect the response of the flame ionization detector, thus understating the actual HC emissions. The behavior of these compounds with respect to adsorption and desorption on the surfaces of the gas sampling system is not known. More studies are needed to understand the organic constituents in the exhaust gases from biodiesel-powered engines before firm conclusions can be drawn regarding HC emissions. Controversy exists concerning the effect of biodiesel on particulate matter emissions.

Biodiesel's cost is the principal barrier, making it less attractive as a diesel substitute. Vegetable oils used in making biodiesel cost about US\$2.00–3.00 per gallon. If the credit for glycerol (a by-product of the biodiesel transesterification process, and a chemical feedstock for many industrial processes) is taken into account, the cost of converting vegetable oils to biodiesel is approximately US\$0.50 per gallon. Thus, the total biodiesel fuel cost is about US\$2.50–3.50 per gallon. This is substantially higher than conventional diesel, which currently costs about US\$0.75 per gallon before taxes. If waste vegetable oil is used, the cost of biodiesel may be reduced to roughly US\$1.50 per gallon. Since the heating value for biodiesel is less than diesel, more fuel must be burned to provide the same work output as diesel fuel, adding to biodiesel's cost disadvantage.

HYDROGEN

Hydrogen may be the cleanest-burning motor fuel, although many of its properties make it difficult to use in motor vehicles. Hydrogen's potential to reduce exhaust emissions stems from the absence of carbon atoms in its molecular structure. The only pollutant produced from hydrogen combustion is NO_x (lubricating oil may still contribute small amounts of HC, CO, and particulates). Hydrogen combustion also produces no direct CO_2 emissions. Indirect CO_2 emissions depend on the nature of the energy source used to pro-

duce the hydrogen. In the long-term event of drastic measures to reduce CO_2 emissions (to help reduce the effects of global warming), hydrogen fuel produced from renewable energy sources would be a possible solution.

Hydrogen can be stored on-board a vehicle as a compressed gas, liquid, or in chemical storage as metal hydrides. Hydrogen can also be manufactured on-board the vehicle by reforming natural gas, methanol, or other fuels, or by the reaction of water with sponge iron.

THE ECONOMICS OF ALTERNATIVE FUELS

Alternative transport fuel economics depend on the cost of production and the additional costs of storage, distribution, and end-use. Production costs are a function of abundance or scarcity of the resources from which the fuel is produced, and the technology required to extract those resources. The additional costs of storage, distribution, and end vehicle use are also important. Gasoline, diesel fuel made from heavy oils, and natural gas require relatively minor changes to existing distribution and end-use systems, while CNG and alcohol fuels require larger modifications.

Organization of Economic Cooperation and Development (OECD) estimates of the costs (production, distribution, and end-use) of alternative fuels are shown in table 4.2. These estimates are based on 1987 costs and technology. According to OECD's International Energy Agency, CNG and Very Heavy Oil (VHO) products could be economically competitive with conventional gasoline at 1987 prices. Methanol and synthetic gasoline made from natural gas were close to competitive, under optimistic assumptions about gas prices. Methanol from coal or biomass, and ethanol from biomass were estimated to have a cost at least twice that of gasoline (IEA, 1990).

A World Bank study (Moreno and Bailey, 1989) found that at crude oil prices of US\$10 per barrel or lower (1988 prices), alternative fuels were generally uncompetitive. At US\$10–20 per barrel, custom-built propane-fueled high mileage

vehicles and retrofitted vehicles using CNG trickle-fill refueling (mostly applicable to captive vehicle fleets—urban buses, taxis, and delivery trucks—with high annual mileage and restricted range) became competitive. At US\$20–30 per barrel, CNG fast-fill and propane-fueled low mileage vehicles would be competitive. Methanol from natural gas becomes competitive above US\$50 per barrel of crude oil, while

Table 4.2: Comparative Costs of Alternative Fuels (1987)

Fuel	Overall Cost (1987 US\$ per barrel-gasoline energy equivalent)
Crude oil (assumed price)	18
Conventional Gasoline	27
Compressed Natural Gas	20-46
Very Heavy Oil Products	21-34
Methanol (from gas)	30-67
Synthetic Gasoline (from gas)	43-61
Diesel (from gas)	69
Methanol (from coal)	63-109
Methanol (from biomass)	64-126
Ethanol (from biomass)	66-101

Source: International Energy Agency.1990. "Substitute Fuels for Road Transport: A Technology Assessment." OECD, Paris.

Table 4.3: Costs of Conventional and Alternative Fuels in the United States.

	Gasoline (a)	Methanol (b)	Ethanol (c)	LPG (c)	CNG(d)	LNG(e)	Hydrogen (f)
Wholesale (\$/galg)	0.51-0.68	0.32-0.42	1.29-1.45	0.25-0.45	0.25-0.50	0.40-0.55	0.25
Wholesale (\$/thermh)	0.41-0.54	0.56-0.74	1.70-1.91	0.29-0.53	0.26-0.52	0.53-0.72	0.85
Retail (\$/gal)	0.97-1.32	0.80-0.92	n/a (i)	0.95-1.10	0.40-0.90	n/a	9.60-16.00
Retail (\$/therm)	0.78-1.06	1.41-1.62	n/a	1.12-1.29	0.41-0.93	n/a	33.10-55.17

(a) Gasoline wholesale and retail prices - Oil & Gas Journal, December 21, 1992, page 114.

(b) Methanol wholesale prices - Oxy-Fuel News, October 5, 1992, page 9.

Methanol retail prices - current California retail prices.

(c) Ethanol and LPG wholesale prices - Oxy-Fuel News, October 5, 1992, pp. 8-9. LPG retail prices - current California retail prices

(d) Wholesale and retail prices - Industry estimates

(e) LNG wholesale prices - Industry estimates

(f) Hydrogen retail prices are based on quotes from industrial gas suppliers.

(g) natural gas and hydrogen are priced in dollars per 100 ft³

(h) Therm = 100,000 Btu

(i) n/a = not currently available at retail outlets

synthetic gasoline and diesel fuel do not become competitive until the price of crude oil reaches US\$70 per barrel. For CNG-fueled vehicles, the high cost of fuel transport in tube trailers suggests that CNG would be competitive at the crude oil prices indicated above only if filling stations are located near a natural gas pipeline or distribution network.

CLIMATE CHANGE

Climate change, or the "greenhouse effect," is a major stimulus for switching to alternative fuels. This change in climate occurs when certain gases allow sunlight to penetrate to the earth but partially trap the planet's radiated infrared heat in the atmosphere. Some of this warming is natural and necessary. Over the past century, however, human activities have increased atmospheric concentrations of naturally occurring water vapor, CO₂, methane, and other infrared-absorbing (greenhouse) gases, and added new and very powerful infrared-absorbing gases to the mixture. Even more disturbing, in recent decades the atmosphere has begun to change at dramatically accelerated rates as a result of human activities. According to a growing scientific consensus, if current emissions trends continue, the buildup of infrared-absorbing gases is likely to turn earth's natural atmospheric greenhouse into a progressively warmer "heat trap." This phenomenon is commonly referred to as "global warming."

Various human activities contribute to climate change. Recent estimates indicate that by far the largest contributor (about 50 percent) is energy consumption, mostly from the burning of fossil fuels. The release of chlorofluorocarbons (CFCs), the second largest contributor to global warming, accounts for approximately another 20 percent. CFCs are known to deplete the stratospheric ozone layer; these stable and long-lived chemicals are also extremely potent greenhouse gases. Deforestation and agricultural activities (especially rice production, cattle raising, and the use of nitrogen fertilizers) each contribute about

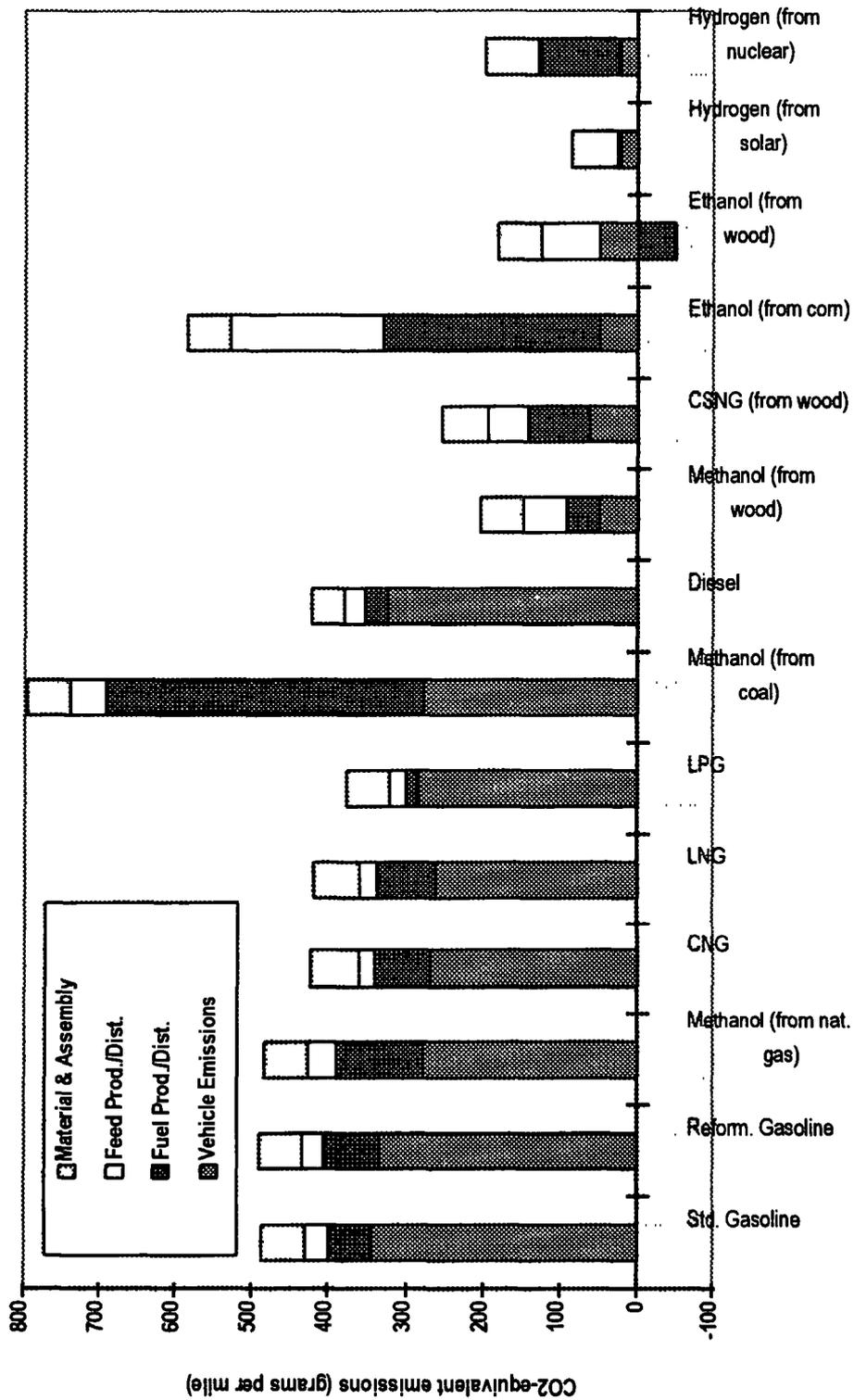
13–14 percent to global warming.

As greenhouse gases accumulate in the atmosphere, they amplify the earth's natural greenhouse effect, profoundly and perhaps irreversibly threatening humankind and the natural environment. While most scientists agree on global warming's overall features, considerable uncertainties still surround its timing, magnitude, and regional impacts. The global climate system is complex, and interactions between the atmosphere and the oceans are still imperfectly understood.

Two recent events have heightened this concern. In late November 1995, the Intergovernmental Panel for Climate Change (IPCC) Working Group 1 concluded that "the balance of evidence suggests that there is a discernible human influence on global climate."² More recently, a provisional report issued by the British Meteorological Office and the University of East Anglia concluded that the earth's average surface temperature climbed to a record high in 1995.³ In spite of commitments by most industrialized countries to stabilize or reduce CO₂ emissions, very little progress has occurred in the transportation sector. Recent strategies such as mandatory increases in fuel economy or substantial increases in fuel taxes have proven disappointing. Biofuels, giving off dramatically lower CO₂ emissions, are therefore emerging as one of the more attractive and less painful approaches to lowering greenhouse gas emissions.

One seminal study released in late 1991 assessed greenhouse gas emissions from a variety of potential fuels; some of the results are summarized in figure 4.1.⁴ This study concluded that in considering total fuel cycle CO₂ emissions (including not only direct vehicle emissions, but fuel production and distribution, feedstock production and distribution, and vehicle materials and assembly), methanol and ethanol produced from wood are among the two most attractive fuels available, exceeded only by solar power. Biomass-based fuels could reduce substantially transportation's contribution to global warming.

Figure 4.1: Greenhouse Gas Emissions from Fuels



Source: U.S. Department of Energy, 1991.

ELECTRIC VEHICLES

Environmental concerns have prompted the use of electric vehicles (EV) in the United States and around the world. UNDP estimates that the emerging and rapidly-growing EV market will go from virtually zero in 1996 to US\$2.5 billion by 2000.⁵ In the United States, California has mandated the target of 10 percent of its fleet being zero emissions (almost certainly electric) by 2003.⁶ Many companies have developed or are developing electric vehicles, some of which (particularly small vehicles such as electric bicycles and motorcycles) can be used in the developing world.

Introducing electric vehicles in the developing world is sometimes advocated as an opportunity to move to environmentally sustainable transportation. There are several encouraging examples in Asia. A demonstration fleet of electric vehicles is already operating in Kathmandu, Nepal.⁷ Electric three-wheelers ("tuk-tuks") are being manufactured in Thailand.⁸ Electric motorcycles have been developed in Taiwan.⁹ USAID has been promoting electric vehicle technology in India.¹⁰ Similar projects have been proposed for Bangladesh.

EV's life-cycle environmental characteristics depend on the fuel used to produce the electricity. Electric power based on hydropower or natural gas results in significantly reduced emissions. Some other fuels (especially coal) may actually produce an increase in overall emissions if used to charge EV batteries, but still have the positive effect of localizing emissions.¹¹

EV technology is presently considered too expensive, although its promoters have expressed ambitions for commercialization in both industrialized and developing countries.^{7,12} High costs and short range (miles per charge) have limited the mass appeal of EVs. New developments in electric battery technology are critical to progress.¹³

Along with battery-powered EVs, other options such as fuel cell technology, which converts fuel energy directly into electricity without combustion,¹⁴ appear very promising but are even more expensive at present. EV technology's potential

to reduce greenhouse gas emissions has been recognized in the Global Environmental Facility's new Transport Sector Operational Programme.¹⁵

FACTORS INFLUENCING LARGE-SCALE USE OF ALTERNATIVE FUELS

1. Introducing alternative fuels requires changes in distribution, marketing, and end-use systems.
2. Apart from the economics, inadequate fuel supply or unreliable distribution systems could adversely affect consumer acceptance of alternative transportation fuels.
3. Experience with the use of ethanol in Brazil and CNG in New Zealand suggests that the main factors influencing large-scale introduction of CNG and alcohol fuels are price competitiveness, feedstock availability and cost (e.g., sugar cane for ethanol or natural gas for CNG), fuel safety and quality standards, a reliable distribution system, and the vehicles' technical quality (driveability, durability, and safety).
4. Brazil's use of ethanol and New Zealand's use of CNG demonstrate that it is possible to develop a large alternative fuels market within a reasonable time frame if the financial incentives are favorable, and efforts are made to overcome industry and consumer uncertainty. In both instances, substantial subsidies had to be offered to private motorists to persuade them to switch to alternative fuels.

ENDNOTES

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CHAPTER 5: IMPLEMENTING A CLEAN FUELS PROGRAM

Implementing a clean fuels program can take many forms, including strict government mandates, fiscal incentives, or some combination of the two. Mandates can focus on fuel quality, vehicle fuel requirements, or fuel pump nozzles. Some of the more common approaches are summarized below (figure 5.1).

IMPROVING FUEL QUALITY

Perhaps the simplest and most direct approach is to rule that some or all grades of fuel meet specific characteristics by a certain date. For example, all stations might be required to provide

at least one grade of unleaded gasoline by a defined date. Refinements of this approach might limit this to only stations pumping a certain volume of fuels. Another approach would require all regular-grade fuel of a certain octane to be unleaded, while allowing the premium grade to remain leaded. Bangkok chose this approach for its clean fuel program by requiring all gasoline to be unleaded by 1996.

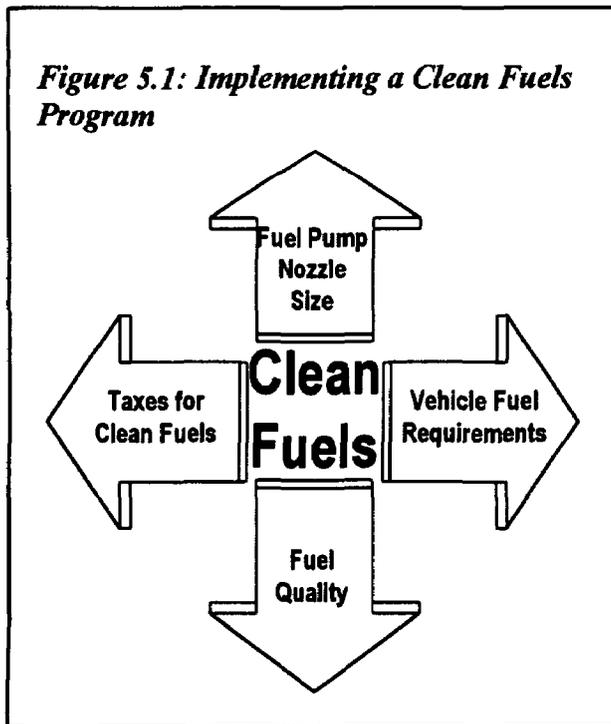
VEHICLE FUEL REQUIREMENTS

Another approach requires that all new vehicles from a specified date onward only be allowed to use fuels meeting certain characteristics (e.g., unleaded gasoline). This approach has been implemented in Singapore, where all new cars are required to operate on unleaded gasoline. This addresses any concerns about valve seat recession and soft valve seats, and eliminates lead emissions from these vehicles. For detailed information regarding international fuel emissions standards, see appendix D.

FUEL PUMP NOZZLE CHARACTERISTICS

As noted earlier, vehicles equipped with catalytic converters require unleaded gasoline to ensure that these systems are not destroyed. When leaded gasoline is cheaper than unleaded, the chances of misfueling are high. To prevent such vehicles from being deliberately or inadvertently fueled with leaded gasoline, cars with catalytic converters can be equipped with filler inlet restrictors or

Figure 5.1: Implementing a Clean Fuels Program



design changes that do not allow leaded fuel nozzles to fit. While this is by no means a fail-safe approach, it is definitely a step in the right direction.

ADOPTING CLEAN FUEL TAX INCENTIVES

Rather than directly mandating unleaded gasoline or low-sulfur diesel fuel, or in addition to this step, many governments have introduced tax policies intended to give the cleaner fuel a lower market price than the dirtier fuel. Theoretically, public demand will then assure the cleaner fuel's availability and use. This strategy can be used in the absence of a sales mandate or as a complement to accelerate clean fuel's market penetration. Hong Kong provides one of the most successful examples of this incentive.

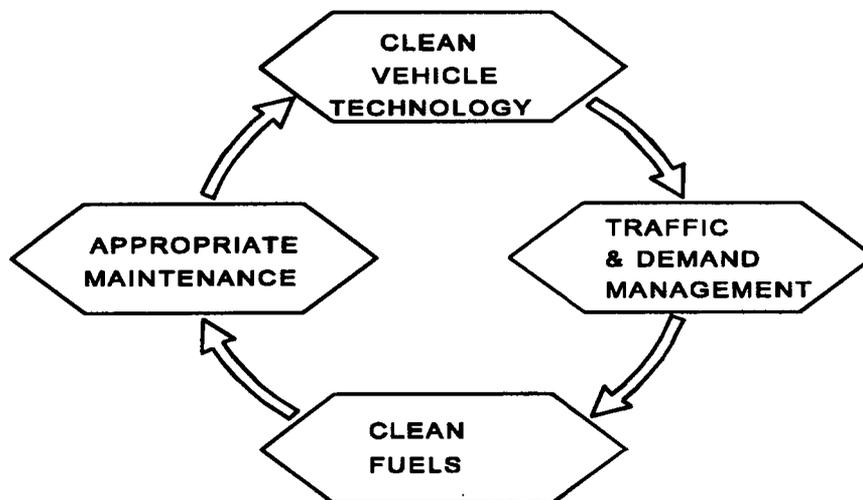
Experience shows that fuel pricing must play a key role in any strategy to encourage cleaner fuels. For example, in the United States during the 1970s and early 1980s, leaded gasoline was consistently less expensive than unleaded. As a result, in spite of fuel nozzle size restrictions and vehicle fuel filler inlet restrictions, many people destroyed their catalytic converters by using leaded fuel.

VEHICLE POLLUTION CONTROL EFFORTS UNDERWAY IN ASIA

A great deal has been learned about reducing vehicle emissions, and this knowledge has been translated into strategies that lower emissions per kilometer driven and reduce actual driving. Both approaches can be used to lessen future air pollution damage in Asian cities.

Generally, a motor vehicle pollution control

Figure 5.2: Elements of a Comprehensive Vehicle Pollution Control Strategy



program's goal is to reduce vehicle emissions to a degree necessary to achieve healthy air as rapidly as possible. This should be accomplished within practical technological, economic, and socially feasible limits. **This goal generally requires a comprehensive strategy encompassing new vehicle emissions standards, cleaner fuels, vehicle maintenance, and traffic and demand management and constraints.** These emissions reduction goals should be achieved in the least costly manner. Exhaust and evaporative motor vehicle emissions standards should be based on a realistic cost-benefit analysis, keeping in view proposed countermeasures' technical and administrative feasibility.

The following **technological approaches**¹ may be used to achieve desired emissions standards:

- fitting new vehicles with emissions control devices and requiring such devices to be retrofitted to existing vehicles;
- modifying fuels or requiring the use of alternative fuels in certain vehicles; and
- traffic and demand management and policy instruments.

However, many of these measures' potential benefits will be lost if they are not buttressed by

regulatory and economic instruments that assure that vehicle owners, manufacturers, and fuel suppliers have sufficient incentives to achieve the desired goals. **A key element of the overall strategy, therefore, must be effective enforcement to ensure adequate compliance with standards.**

Several jurisdictions in Asia have successfully implemented some or all of these strategies. Specific examples in Hong Kong, Singapore, South Korea, Taiwan, and Thailand illustrate some of these efforts.

Bangkok, Thailand

In response to the serious air pollution threat, Thailand's *Seventh Plan* has placed a high priority on improving air quality. Definite targets have been set to control particulates (SPM), carbon monoxide (CO), and lead in Bangkok. Based on a careful review of available air quality data, it is estimated that roadside emissions of particulates, CO, and lead must be reduced by 85 percent, 47 percent and 13 percent, respectively, if Bangkok is to achieve acceptable air quality.² To date, there is no evidence of an ozone or nitrogen dioxide (NO₂) problem. However, since certain hydrocarbons are known to be toxic, it is prudent to adopt measures that will reduce these emissions as well.

One-hour concentrations of CO in congested streets have been on the decline since 1992, but 8-hour averages have not similarly declined. This suggests that during peak traffic hours new cars and emissions control technology may lessen the air quality problem, as the traffic volume is the same. However, the peak hours may be longer; thus the longer averaging time (8-hour) may produce stable or increasing results. The high values observed for the 8-hour averages are about 20 mg/m³. Similarly, curbside 8-hour average concentrations of CO are close to and sometimes exceed Thai standards (20 mg/m³). Concentrations as high as 25 mg/m³ have been recorded.

A U.S. Agency for International Development (USAID) study (1990) attempted to rank environmental health risks to Bangkok's 5.5 million residents. It was estimated that 270,000 people

are at moderate risk for health effects associated with CO (angina in people with chronic cardiovascular disease), and 1.3 million people at mild risk (inability to concentrate and headaches for people in the general population).³

A World Bank study (1992) indicates that if Bangkok's ambient concentrations of SPM and lead were reduced by 20 percent from 1992 levels, the midpoint estimates of the annual health benefits from less sickness would be US\$1 to 1.6 billion. Benefits in terms of lower mortality would amount to between US\$300 million and 1.5 billion. The study assigned various monetary values to the estimated health risks found by the USAID study, and estimated an economic benefit of US\$10.7 million annually from CO reduction in Bangkok.⁴

Bangkok's current program. A number of measures have been adopted to mitigate air pollution problems caused by the transport sector. These are aimed not only at controlling exhaust gas emissions, but also at improving fuel and engine specifications, implementing an in-use vehicle inspection and maintenance program, improving public transport through mass transit systems, and improving traffic conditions through better traffic management.

The following measures have been introduced to reduce vehicle emissions:

1. Introducing unleaded gasoline at prices lower than leaded gasoline (effective May 1991).
2. Reducing the maximum allowable lead in gasoline from 0.4 to 0.15 grams per liter (effective January 1, 1992). Ambient lead levels have declined in recent years due to reduced lead content in gasoline and the increased use of unleaded gasoline.
3. Phasing out leaded gasoline entirely (January 1, 1996).
4. Reducing the sulfur content of diesel fuel sulfur from 1.0 to 0.5 percent by weight (by April 1992 in the Bangkok Metropolitan Area, and nationwide after September 1992); and making the use of low-sulfur diesel fuel mandatory in Bangkok (since September 1993).

5. Reducing the diesel fuel T_{90} from 370°C to 357°C (by April 1992 in the Bangkok Metropolitan Area, and nationwide after September 1992).
6. Requiring all new cars with engines larger than 1600 cubic centimeters to meet ECE R-83 standards (effective January 1993); and all cars required to comply after September 1993.
7. Converting taxis and Tuk-Tuks to operate on liquefied petroleum gas (LPG).
8. Introducing ECE R40 requirements for motorcycles (effective August 1993), followed soon afterward by ECE R40.01; the government then decided on a third level of controls which began to be phased in during 1995.
9. Implementing ECE R49.01 standards for heavy-duty diesel engine vehicles.
10. Reducing diesel fuel sulfur levels from the current 0.5 percent by weight to 0.25 (by 1996), and 0.05 by the year 1999.

Currently, noise and emissions testing is mandatory under the Land Transport Department's (LTD) general vehicle inspection program. All new vehicles are subject to such inspection. Of in-use vehicles, only those vehicles registered under the Land Transport Act (buses and heavy-duty trucks) and commercial vehicles registered under the Motor Vehicles Act (taxis, Tuk-Tuks, and rental vehicles) are subject to inspection during annual registration renewals. It is expected that the LTD will soon require all in-use vehicles to be inspected. Private inspection centers are being licensed. Vehicles in use for ten or more years are subjected to an annual inspection, while newer vehicles will be subjected to inspection at different time periods, to be determined by the LTD.

Future Plans. Further investigations underway will introduce more stringent standards for motorcycles and light and heavy trucks, and lead to the further purchase of compressed natural gas (CNG) buses to reduce the smoke problem.

As a comprehensive motor vehicle pollution control strategy has been introduced in Bangkok, the most critical data needs appear to be those related to motorcycle and diesel vehicle particulate emissions factors. In addition, as the new air qual-

ity monitoring network is deployed it will be critical to periodically update the air quality targets.

Conclusions. Bangkok, like many other megacities, has serious air pollution problems associated with energy use in the transport sector. Several factors, including population growth and rapid economic expansion, are fundamental issues that need to be addressed in any long-term planning. Rapid industrialization and urbanization, coupled with a previous lack of land-use planning, have contributed to atmospheric pollution associated with the transport sector. This problem has been intensified by inadequate road infrastructure for the rapidly growing vehicle population, and the lack of a mass transport system to offer a viable substitute for private vehicles. These factors tend to push people to rely more on their private vehicles (contributing to congestion), rather than drive less.

It is recognized that this problem can be alleviated through several measures: source reduction through improvement of fuel quality, inspection and maintenance programs, vehicle standards, and traffic and demand management (including a good mass rapid transit system). A great deal of policy work needs to be done to understand travel demand (demand-side management).

Singapore

In Singapore, motor vehicle emissions are a significant source of air pollution. The vehicle population has been steadily increasing over the past decade as a consequence of rapid urbanization and economic growth. At the beginning of 1993, the motor vehicle population stood at approximately 550,000. Singapore's Clean Fuels Program has eight major components: land transport policy, mobile source controls, traffic management measures, vehicle registration and licensing, a vehicle quota system, the weekend car scheme, the area licensing scheme, and public transportation.

Singapore's **land transport policy** strives to provide free-flowing traffic within the constraints of

limited land. A four-pronged approach has been adopted to achieve this objective:

1. Minimizing the need to travel, through systematic town planning.
2. Building an extensive and comprehensive network of roads and expressways, augmented by traffic management measures, to provide quick accessibility to all parts of Singapore.
3. Promoting a viable and efficient public transport system, integrating both the Mass Rapid Transit (MRT) and bus services.
4. Managing the number and operation of vehicles to prevent congestion on the road.

Mobile Source Controls. Singapore's strategy to reduce pollution from motor vehicles is a two-pronged approach. The first is to improve engines and fuel quality to reduce emissions; and the second is to use traffic management measures to control the vehicle population and fuel consumption. The Pollution Control Department works closely with the Registry of Vehicles to implement this strategy.

- During 1981–87, the lead content of gasoline was gradually reduced from 0.8 to 0.15 grams per liter. The use of unleaded gasoline was promoted in February 1990 through a differential tax system that made unleaded gasoline S\$0.10 cheaper per liter than leaded gasoline at the pump. All gasoline-driven vehicles registered for use in Singapore after July 1991 were required to use unleaded gasoline. These measures resulted in the greater use of unleaded gasoline. About 57 percent of all gasoline sold in Singapore by the end of 1993 was unleaded.
- The sulfur content in diesel fuel was first limited to 0.5 percent by weight, and has been reduced to 0.3 percent by weight since July 1996.
- Motor vehicle emissions standards have been progressively tightened since 1984, and the standards currently in force are the European Union Consolidated Emissions Directive 91/441 and Japanese emissions standards (Article 31 of Safety Regulations for Road Vehicles) (see appendix D).

- Since October 1992, motorcycles and scooters have been required to comply with U.S. emissions standards before they can be registered for use in Singapore.
- Since January 1991, all diesel vehicles have been required to comply with smoke standards stipulated in UN/ECE Regulation No. 24.03 before they can be registered for use in Singapore.
- All in-use vehicles are required to undergo periodic inspections to check their roadworthiness and idling exhaust emissions. Vehicles that fail inspection are not allowed to renew their road tax.

Traffic Management Measures. Singapore, a city-state with a large population living on a small land mass, is unique in many ways. Urbanization, industrialization, and infrastructural development are still progressing in earnest, fueled by a growing economy. This combination of factors shows a potential for serious environmental problems from both stationary and mobile sources, if the sources are not managed or controlled properly. The need to manage traffic flow has given rise to a unique set of traffic management measures.

Vehicle Registration and Licensing. The expense of owning and operating a vehicle in Singapore has discouraged excessive growth in the vehicle population. Car owners wishing to register their cars must pay a 45 percent import duty on the car's open market value (OMV), a registration fee of S\$1,000 for a private car (S\$5,000 for a company-registered car), and an Additional Registration Fee of 150 percent of the OMV.

In addition, car owners pay annual road taxes based on the vehicle's engine capacity. Road tax on company-registered cars is twice as high as for privately-owned vehicles. Diesel vehicles are charged a tax six times greater than the road tax on an equivalent gasoline vehicle.

To encourage drivers to replace their old cars with newer, more efficient models, a Preferential Additional Registration Fee (PARF) system was introduced in 1975. Private car owners who

replace their cars within ten years are given PARF benefits that can be used to offset a new car registration fee. For used cars registered on or after November 1, 1990, PARF benefits vary according to the age of the vehicle at deregistration. For cars registered before November 1, 1990, a fixed PARF benefit is given upon deregistration based on the car's engine capacity. To provide a higher PARF benefit to car owners who deregister their cars before ten years, all PARF-eligible cars registered on or after November 1990 receive higher fees if the vehicle is newer.

Vehicle Quota System. As high taxes alone were not keeping vehicle population growth at an acceptable rate, a vehicle quota system was introduced to achieve that objective. Since May 1990, any person wishing to register a motor vehicle must first obtain a vehicle entitlement in the appropriate vehicle class, through monthly bidding. Successful bidders pay the lowest successful bid price of the respective category in which they bid. A vehicle entitlement is valid for ten years from the vehicle's registration date. On the entitlement's expiration, if the owner wishes to continue using the vehicle, the entitlement must be revalidated for another five or ten years by paying a revalidation fee (pegged at 50 percent or 100 percent of the prevailing quota premium).

Weekend Car Scheme. The weekend car scheme was introduced in May 1991 to allow people to own private cars without adding to traffic congestion during peak hours. Cars registered under this scheme enjoy substantial tax concessions, including a 70 percent reduction in road tax and a registration tax rebate of up to S\$15,000. Weekend cars are identified by their red license plates, fixed in place with a tamper-evident seal. They can only be driven between 7 p.m. and 7 a.m. during the week, after 3 p.m. on Saturdays, and all day on Sundays and public holidays. Weekend cars can be driven outside those hours but owners must display a special day license. Each weekend car owner is given five free day licenses per year and can buy additional ones at S\$20 each.

The **Area Licensing Scheme (ALS)** was introduced in June 1975 to reduce traffic congestion in the city during peak hours. At that time it only affected passenger cars. The scheme has since been modified to include all vehicles except ambulances, fire engines, police vehicles, and public buses.

Public transportation in Singapore is widely available and includes a mass rapid transit (MRT) system, a comprehensive bus network, and over 13,000 taxis.

Conclusions. Aside from regulations on engines and fuel quality, traffic control measures have significantly contributed to Singapore's air quality. Although the present measures appear adequate, Singapore will continue to investigate more improvements. Pilot studies of three electronic road pricing systems are being carried out in Singapore, and the most suitable system will be selected for implementation in 1997.

Hong Kong, China

Hong Kong's vehicle pollution control effort continues to focus on diesel particulate, currently the most serious pollution problem. Motor vehicles are said to be responsible for approximately 50 percent of PM_{10} emissions (see appendix D).

Current Program. The sulfur level of diesel fuel has been reduced to 0.2 percent by weight (as of April 1995), and there are plans to lower it to 0.05 percent (April 1997).

Diesel vehicle emissions standards were also tightened in April 1995. After that date, all new passenger cars and taxis were required to comply with 1990 U.S. standards ($PM = 0.12$ grams per kilometer, $NO_x = 0.63$), European Union Step 1 standards (93/59/EEC $PM = 0.14$, $HC + NO_x = 0.97$), or Japanese standards ($PM = 0.34$, $NO_x = 0.72$ for vehicles weighing less than 1.265 tons or 0.84 for those above). Similar requirements will apply to all light and medium goods vehicles and light buses. Emissions standards for small diesel vehicles will be tightened to EURO 2 stan-

standards starting April 1998 (96/69/EMPM 0.08 and 0.10, HC + NO_x = 0.7 and 0.9 for indirect injection and direct injection engines, respectively). For goods vehicles and buses with a design weight of 4.0 tons or more, starting April 1997, either the 1994 U.S. standards (PM = 0.13 grams per kWh, NO_x = 8.04) or the EURO 2 standards (PM = 0.15; NO_x = 7.0 for all engines) will apply.

The in-use smoke limit, now based on the EEC free acceleration test (72/306/EEC), was 60 HSU; in certification, the limit was lowered to 35 HSU starting April 1997.

Encouraged by a price differential of HK\$1 per liter for unleaded gasoline as compared to leaded, by 1997 unleaded gasoline represented 80 percent of total gasoline sales. The benzene content of unleaded gasoline is only 3.44 percent, virtually the same as leaded gasoline (regulation requires it to be less than 5.0 percent).

Future Plans. An analysis of motor vehicle-related urban particulates indicates that 14 percent come from buses, 33 percent from goods vehicles, 51 percent from diesel vehicles weighing under 4.0 tons, and the remaining 2 percent comes from gasoline vehicles.

- As a matter of policy, Hong Kong is looking for ways to reduce diesel vehicle mileage. A government working group has been formed to study the technical feasibility of natural gas vehicles. The short-term focus is on LPG-fueled taxis, while other natural gas vehicles are being investigated.
- Advancement in new technologies, such as electrical vehicles, are also being monitored closely. The Government has waived the First Registration Tax (which can amount to as much as 50 percent of a vehicle's price) to encourage the introduction of electrical vehicles into Hong Kong.
- The government plans to implement an inspection and maintenance program for diesel vehicles in the near future.
- Hong Kong also remains interested in the possibility of retrofitting buses with either emissions catalysis or diesel particulate filters.

South Korea

A series of recent amendments in the Air Quality Control Law will gradually tighten South Korea's vehicle emissions standards, as summarized in tables 5.1 and 5.2.

Diesel fuel sulfur levels were reduced to a maximum of 0.4 percent by weight between February 2, 1991 and December 31, 1992; to 0.2 during January 1, 1993–December 31, 1995; and 0.1 thereafter. Korea is also investigating possible improvements to their inspection and maintenance (I/M) program, including the possible addition of the IM240 test procedure.

There is ongoing research in the use of diesel particulate filters. On-road testing of prototype systems in operating buses is presently under evaluation.

Taiwan (China)

The Taiwan Environmental Protection Agency (TEPA) has developed a comprehensive approach to motor vehicle pollution control. Building on its early adoption of 1983 U.S. standards for light-duty vehicles (starting July 1, 1990) it recently moved to 1987 U.S. requirements, including the 0.2 grams of particulates per mile standard, as of July 1, 1995. Heavy-duty diesel particulate standards almost as stringent as 1990 U.S. emissions standards (6.0 grams per brake horsepower-hour NO_x and 0.7 grams of particulate, using the U.S. transient test procedure) became effective July 1993. In July 1997, 1994 U.S. standards (5.0 NO_x and 0.25 particulates) will be adopted. Currently diesel fuel contains 0.3 percent by weight of sulfur, and a proposal to reduce levels to 0.05 percent by 1997, is under consideration.

In December 1992, the Executive Yuan approved increases of up to 1,700 percent for the amount of fines to be levied on motorists who violate the Air Pollution Control Act. The new fine schedule raises the maximum motor vehicle pollution fine from NT\$138 to NT\$2,357. All forms of motorized transportation are included in the new fine schedule, including airplanes,

boats, and power water skis. The new fines took effect early in 1993.

Clearly, the most distinctive feature of Taiwan's program is its motorcycle pollution control effort, which reflects just how much motorcycles dominate the vehicle fleet, and the extent of the resulting emissions.

- The first standards for new motorcycles were imposed in 1984—8.8 grams per kilometer for CO, and 6.5 grams per kilometer for HC and NO_x combined, using the ECE R40 test procedure.
- In 1991, the limits were reduced to 4.5 grams of CO per kilometer, and 3.0 for HC and NO_x combined. These requirements were phased in over a two-year period, and by July 1993, were applied to all new motorcycles sold in Taiwan. As a result of these requirements, four-stroke motorcycle engines have been re-

designed to use secondary air injection, and all new two-stroke motorcycles are now fitted with catalytic converters.

- Since 1992, electric motorcycles have been available; however, sales have been modest.
- Motorcycle durability requirements were imposed in 1991. All new motorcycles are required to demonstrate the ability to meet emissions standards for a minimum of 6,000 kilometers.
- Since 1991, all new motorcycles must be equipped with evaporative controls.
- In order to reduce the pollution from motorcycles, TEPA is actively promoting a motorcycle inspection and maintenance (I/M) system. In the first phase (February–May 1993), TEPA tested approximately 113,000 motorcycles in Taipei City. Of these, 49 percent were clean, 21 percent were marginal, and 30 percent failed.

Table 5.1: South Korea: Emissions Standards For New Gasoline and LPG Vehicles

Vehicle Type	Date Of Implementation	Test	CO	NOx	Exhaust HC	Evap HC (g/test)
Small Size Car*	1987 7/1	CVS-75g/km	8.0	1.5	2.1	4.0
	2000 7/1	CVS-75	2.11	0.62	0.25	2.0
Passenger Car	1980 1/1	10-Mode	26.0	3.0	3.8	-
	1984 7/1	10-Mode	18.0	2.5	2.8	-
	1987 7/1	CVS-75	2.11	0.62	0.25	2.0
	2000 1/1	CVS-75	2.11	0.25	0.16	2.0
Light Duty Truck**	1987 7/1	CVS-75	6.21	1.43	0.50	2.0
	2000 1/1	CVS-75@	2.11	0.62	0.25	2.0
	2000 1/1	CVS-75@@	6.21	1.43	0.50	2.0
Heavy Duty Vehicle	1980 1/1	6-Mode	1.6%	2200 ppm	520 ppm	-
	1987 7/1	U.S. Transient	15.5	10.7	1.3	4.0
	1991 2/1	13 Mode	33.5	11.4	1.3	-
	2000 2/1	13 Mode	33.5	5.5	1.4	-

Notes:

* Less than 800 cc of Engine Displacement

@ GVW < 2 Tons

** GVW < 3 tons

@@GVW Between 2 and 3 Tons

- Between December 1993 and May 1994, approximately 142,000 motorcycles were inspected with 55 percent passing (up 6 percent from the earlier program), and 27 percent failed (dropping 3 percent). The most common repair for failing motorcycles was replacement of the air filter, at an average cost of NT\$20.
- To further control motorcycle emissions, TEPA has drafted the Third Stage Emissions Regulation, to be implemented from 1998. The new standards will lower CO to 3.5 grams per kilometer, and HC plus NO_x to 2 grams, and the durability requirement will be raised to 20,000 kilometers. The market share for electric-powered motorcycles will be mandated at 5 per-

Table 5.2: South Korea: Emissions Standards For New Diesel Vehicles

Vehicle Type	Date of Implementation	Test	CO	NO _x	HC	PM	Smoke
Passenger Car	1980 1/1	Full Load	-	-	-	-	50%
	1984 7/1	6-Mode	980 ppm	1000/590*	670	-	50%
	1988 1/1	6-Mode	980	850/450	670	-	50%
	1993 1/1	CVS-75	2.11	0.62	0.25	0.12	-
	1996 1/1	CVS-75	2.11	0.62	0.25	0.08	-
	2000 1/1	CVS-75	2.11	0.62	0.25	0.05	-
Light Duty Truck**	1980 1/1	Full Load	-	-	-	-	50%
	1984 7/1	6-Mode	980	1000/590	670	-	50%
	1988 1/1	6-Mode	980	850/460	670	-	50%
	1993 1/1	6-Mode	980	750/350	670	-	40%
	1996 1/1	CVS-75	6.21	1.43	0.5	0.31(0.16)@	-
Light Duty Truck < 2 Tons	2000 1/1	CVS-75	2.11	0.75	0.25	0.12	-
All Other Light Duty Trucks	2000 1/1	CVS-75	6.21	1.00	0.5	0.16	-
Heavy Duty Vehicle	1980 1/1	Full Load	-	-	-	-	50%
	1984 7/1	6-Mode	980	1000/590	670	-	50%
	1988 1/1	6-Mode	980	850/450	670	-	50%
	1993 1/1	6-Mode	980	750/350	670	-	40%
	1996 1/1	13-Mode	4.9	11.0	1.2	0.9	35%
	2000 1/1	13 Mode	4.9	6.0	1.2	0.25 (1@@)	25%

Notes:

* Direct Injection/Indirect Injection

** GVW < 3 tons

@ GVW < 2 Tons

@@ City Bus Only

cent. In addition, TEPA will extend the periodic motorcycle I/M program.

COMPREHENSIVE PROGRAMS: THE UNITED STATES EXPERIENCE

Since 1970, the United States has adopted an aggressive strategy to reduce auto emissions and improve air quality. This strategy has many elements, including unleaded gasoline, tighter standards for new vehicles, in-use vehicle inspection and maintenance programs, and most recently, reformulated and low-volatility gasoline. As a result, over the past 25 years, on-highway cars' emissions rates have declined dramatically. As newer vehicles equipped with advanced emissions controls replaced older, more-polluting ones, there has been a clear downward trend in emissions of all major pollutants. This is especially encouraging in light of the continued rapid growth in vehicles and vehicle-miles traveled by cars during this same period. There were 50 million more cars on U.S. highways in 1990 than in 1970. Had emissions per mile not been lowered, passenger cars in 1990 would have emitted 65 percent more CO, HC, and NO_x than in 1970. In other words, as illustrated in table 5.3, passenger car CO was reduced from 68 million metric tons to 27, instead of climbing to 112 tons.

Figure 5.3 illustrates auto emissions reductions to date: 60 percent for CO; 70 percent for HC; and 46 percent for NO_x. Lead emissions from all highway vehicles have also been reduced dramatically, and between 1970 and 1993, highway vehicle lead emissions declined from 171,960 to 1,380 short tons. This example best illustrates that a strong motor vehicle pollution control program can be effective.

CONCLUSIONS

As the above examples illustrate, substantial efforts to address motor vehicle pollution have been made and are continuing throughout many Asian countries. Several conclusions can be drawn from these efforts:

- There are many comprehensive motor vehicle pollution control programs in the Asia region.
- A wide variety of strategies have been implemented and tailored to the particular problems and capabilities of a particular country or city—one size does not fit all.
- In virtually every serious effort to reduce motor vehicle pollution, cleaner fuels, especially unleaded gasoline and lower-sulfur diesel fuel, have played a critical role.

ENDNOTES

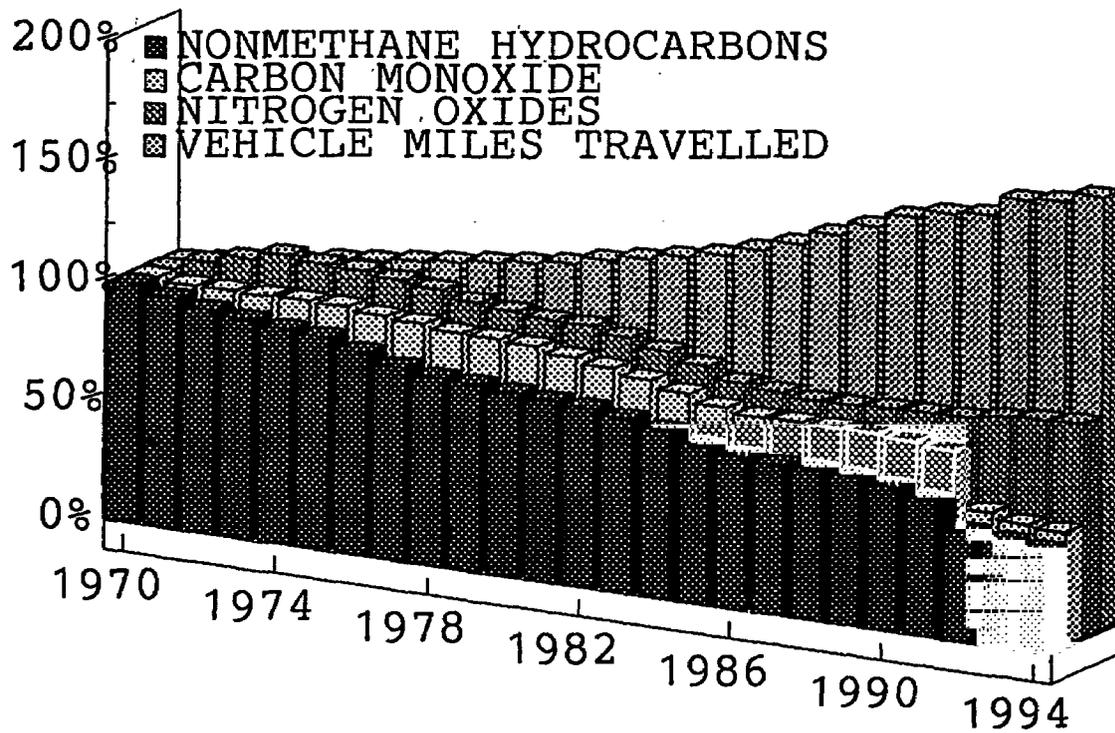
1. See appendices B and C for a review of gasoline- and diesel-fueled vehicle pollution control technologies, respectively.
2. These emissions, especially particulates, come from many sources in addition to mobile sources, which will need to be controlled as well. It is assumed in this first order analysis that the same percentage reduction will be needed from all sources, including mobile sources, to achieve the required overall emissions reduction.
3. U.S. Agency for International Development. "Ranking Environmental Health Risks in

Table 5.3: Emissions Trends In The United States (1970–90): Passenger Cars (tons per year)

	Carbon Monoxide	Hydrocarbons	Nitrogen Oxides
1970 Actual	67.9	8.87	4.36
1990 Actual	26.9	2.65	2.34
1990 Potential*	112.0	14.6	7.2

*What would have occurred had pollution controls not been required during this period.

Figure 5.3: Trends in Emissions from U.S. Cars (normalized to 1970 levels)



Bangkok, Thailand," Vols. 1 & 2, Working Paper, 1990.

4. E. Shin et. al. "Economic Valuation of the Urban Environment with Emphasis on Asia

and Non-Productivity Approaches," draft Paper prepared for UNDP/World Bank/UNCHS Urban Management Program, 1992.

CHAPTER 6:

CONCLUSIONS AND RECOMMENDATIONS

In the last decade, Asian cities have undergone a tremendous growth in industrial output and vehicle population. This growth has worsened air pollution in metropolitan areas, and unless corrective actions are taken to improve the current air quality situation, environmental damage and human health impacts will undermine economic growth. Motor vehicle pollution is a primary contributor to air pollution in all the major cities in Asia. There is considerable evidence that tighter emissions standards in new cars, oxygenated and reformulated gasoline, and alternative fuels will help reduce vehicular emissions. Nevertheless, a number of obstacles must be overcome before these changes can be put into place on a large enough scale to make a measurable difference in air quality. This report provides technical options for implementing a clean fuels program in Asia.

CONCLUSIONS

1. Because motor vehicle populations in most Asian cities continue to grow at rates often exceeding 10 percent per year, serious air pollution problems can be expected in the future.
2. Many Asian countries are making substantial efforts to address their motor vehicle pollution problems. Several conclusions can be drawn from these efforts:
 - (a) A wide variety of strategies are being implemented, often tailored to a particular city or country's problems and capabilities. There is a recognition that **"one size does not fit all."**
 - (b) In every serious effort to reduce motor vehicle pollution, **cleaner fuels**—especially unleaded gasoline and lower-sulfur diesel fuel—have played a critical role.
3. A growing body of data on lead's adverse effects on health, especially in young children, indicates there may be no "safe" level. Reduced lead in gasoline has been shown to reduce children's risk of behavioral problems, lower IQs, decreased ability to concentrate, and for adults, blood pressure-related health issues.
4. Lead scavengers that accompany leaded gasoline have been identified as human carcinogens; eliminating gasoline lead will also reduce this cancer risk.
5. Studies in Europe and the United States show that gasoline lead is responsible for about 90 percent of airborne lead, and that 1 microgram per cubic meter of ambient lead causes a 1–2 microgram per milliliter increase in blood lead levels. This is in addition to lead that may be found in food, drinking water, and other sources. This burden can vary significantly from country to country.
6. Hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter cause or contribute to a wide range of adverse impacts on public health and general well-being, including increased angina attacks in vulnerable individuals; greater susceptibility to respiratory infection; more respiratory problems in school children; increased airway resistance in asthmatics; and eye irritation. Furthermore, these emissions are known to impair crop growth and destroy lakes and forests. In

addition to their direct adverse health effects, HC and NO_x contribute to the formation of photochemical smog and ozone, known to cause many adverse effects.

7. A direct strategy to eliminate lead in gasoline is to progressively ban the use of leaded gasoline; several countries, including Thailand, have adopted this strategy.
8. Concerns have been raised regarding potential valve seat recession in older vehicles with "soft" valve seats if unleaded gasoline is used. However, real-world evidence indicates that this is not a serious problem.
9. Tax policies that price unleaded fuel significantly below leaded fuel, as done in Hong Kong and Singapore, have also been found to be very effective in stimulating the sales of unleaded fuel.
10. While significantly reducing CO, the use of oxygenates such as MTBE in cold temperature environments has raised concerns regarding adverse health effects in certain susceptible individuals. Studies by USEPA and several U.S. states have failed thus far to identify a serious problem, although additional research is ongoing.
11. There is a clear worldwide trend toward lower levels of sulfur in diesel fuel. At a minimum, this reduces particulate emissions from diesel vehicles. Recent European studies indicate that for every 100 ppm reduction in sulfur, there will be a 0.16 percent reduction in particulate from light-duty vehicles and a 0.87 percent reduction from heavy-duty vehicles. Sulfur in fuel also contributes to sulfur dioxide (SO₂) in the atmosphere.
12. Other diesel fuel properties such as volatility, aromatic content, and additives can also have positive or negative effects on diesel

vehicle emissions. Raising the cetane number appears to have positive impacts on emissions.

13. Some alternative fuels, such as natural gas, do offer the potential for large, cost-effective reductions in pollutant emissions, in specific cases. Air-quality claims for alternative fuels, however, must be carefully evaluated, because in many cases similar or even greater emissions reductions can be obtained with conventional fuels and more advanced emissions control systems. Which approach is the most cost-effective depends on the conventional and alternative fuels' relative costs.

RECOMMENDATIONS

1. Encourage the use of lead-free gasoline and catalytic converters.
2. Encourage tax policies that price unleaded gasoline lower than leaded fuel.
3. Encourage gasoline reformulation by modifying parameters such as volatility, oxygenates, sulfur levels, and hydrocarbon mix.
4. Reduce the sulfur content of diesel fuels to 0.05 percent by weight.
5. Promote an Inspection and Maintenance (I/M) Program. Emissions reductions can occur simultaneously with improvements in fuel economy and reductions in vehicle maintenance costs. Reduced maintenance as a result of using unleaded rather than leaded gasoline can save about Can\$0.02 per liter.
6. Encourage the use of alternative fuels including methanol, ethanol, biodiesel, compressed natural gas, liquefied petroleum gas, electricity, hydrogen, synthetic liquid fuels derived from hydrogenation of coal, and various fuel blends, such as gasohol.

APPENDIX A: ADVERSE EFFECTS FROM VEHICLE-RELATED POLLUTION

Cars, trucks, motorcycles, scooters, and buses emit significant quantities of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and fine particles (PM₁₀). Leaded gasoline, where it is still used, is a significant source of lead in urban air. As a result of these emissions, many major cities around the world are severely polluted. This section will review some of the health impacts of these pollutants.

LEAD

During the last two decades, there has been an explosion of knowledge about the adverse health impacts of long-term exposure to low levels of ambient lead.^{1,2} In response to this growing body of data, most industrialized countries, and several developing countries, have introduced unleaded gasoline. Several countries have already prohibited the use of leaded gasoline entirely.

Lead's toxic properties at high concentrations have been known since ancient times, as lead has been mined and smelted for more than 40 centuries. Although precaution regarding lead's use has been widespread for centuries, only recently has lead's adverse impacts at very low levels been fully appreciated. Some of the most innovative work in this area was the 1979 report by Dr. Herbert Needleman which showed that children with high levels of lead accumulated in baby teeth experienced more behavioral problems, lower IQs and decreased ability to concentrate.³ More recent evidence indicates that it is not only the length and severity of lead exposure that affects health damage, but at what age exposure begins.

This is especially important because, "[O]f all the persons in the community, the newborn child is the most prone to injury from overexposure to lead for several reasons, and the damage that may be caused then will have the greatest long-term social and economic consequences."⁴ Another study which monitored 249 children from birth to two 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 at lower levels.⁵

A series of studies in the United Kingdom confirmed these findings.⁶ Even after taking 15 social factors into account, an IQ number deficit of three was consistently found. While these statistics are not necessarily significant in any individual study (which is largely influenced by the size of the sample, among other factors), the body of data consistently shows such effects.

In addition, Dr. Winneke (Germany) offered further evidence that "neuropsychological effects are causally related to very low blood lead levels."⁷ While these effects may not be dominant in any particular instance, they are very real and preventable.

Several comprehensive studies regarding the health impacts of lead have been conducted and the major conclusions are summarized below.

The U.S. National Academy of Sciences (1980)

The U.S. National Academy of Sciences (NAS) study "Lead in The Human Environment" reported, "[T]he evidence is convincing that exposures to levels of lead commonly encountered in urban environments constitute a significant haz-

ard of detrimental biological effects in children, especially those less than three years old. Some small fraction of this population experiences particularly intense exposures and is at severe risk." Following that report, NAS recommended, "[A] serious effort should be made to reduce the baseline level of exposure to lead for the general population of the United States."⁸

The U.S. Environmental Protection Agency

The U.S. Environmental Protection Agency (USEPA) summarized its results as follows: "The majority of the comments emphatically rejected the proposition that lead was no longer a public health problem. Sixty-four comments were received from the professional health community and academia. Sixty of these opposed any loosening of the lead standard, and many suggested that tighter controls would be desirable. Thirty-two comments were received from local and state governments. All of these supported retention of the current standard to protect the citizen's health. Most of the commenters pointed to previous studies, as well as their own experiences, to demonstrate that lead has an adverse effect on people at very low dosages, and that the more the problem is studied the lower the **acceptable level** of lead becomes. They concluded that protection of public health and welfare demands that all reasonable steps be taken to eliminate lead from the environment."⁹ In October 1982, USEPA decided as a result of this review to reduce the amount of lead in gasoline even further.

Based on the growing body of data showing the adverse effects of lead, in 1985 USEPA reduced the maximum allowable lead content in leaded gasoline to 0.1 grams per gallon. As part of that rulemaking, USEPA uncovered evidence linking lead in the blood to high blood pressure.¹⁰

The U.S. Court of Appeals (1983)

The U.S. Court of Appeals completed its review of USEPA's decision to lower gasoline lead levels. In its opinion, the Court stated that, "[T]here

is compelling evidence that gasoline lead is a major cause of lead poisoning in young children." In making this assessment, the Court found, "[R]ecent studies suggest that the recognized danger point of 30 micrograms per deciliter is too high and that lead reduces intelligence at blood lead levels as low as 10–15 micrograms per deciliter... [O]ther studies have correlated blood lead levels of 10–15 micrograms per deciliter with altered brain activity." The Court concluded that, "[T]he demonstrated connection between gasoline lead and blood lead, the demonstrated health effects of blood lead levels of 30 micrograms per deciliter or above, and the significant risk of adverse health effects from blood lead levels as low as 10–15 micrograms per deciliter, would justify USEPA in banning lead from gasoline entirely."¹¹

United Kingdom, The Royal Commission on Environmental Pollution (1983)

In 1983, the Royal Commission reported that "[T]he safety margin between the blood lead concentrations in the general population and those at which adverse effects have been proven is too small... it would be prudent to take steps to increase the safety margin of the population as a whole." It continued that, "[M]easures should be taken to reduce the anthropogenic dispersal of lead wherever possible..."¹²

Most recently, British researchers reviewed every epidemiological study on lead and IQ published since 1979 that examined over 100 children, and measured IQ as a function of blood or tooth lead levels. Based on a meta-analysis of all the data, they concluded that a doubling of body lead burden from 10 to 20 micrograms per deciliter in blood levels was associated with a mean fall of about 1–2 IQ points.¹³

In summary, the available evidence indicates that "[T]here is no known physiological function served by lead in mammalian metabolism. As far as cells are concerned, each molecule of lead has the potential to disrupt the chemical basis of normal cellular function. For nerve cells, this inter-

ference is particularly destructive because communications between cells in the brain depends upon precisely controlled movements of such molecules such as calcium, sodium, potassium and chloride. Lead can interfere, on a molecule by molecule basis, with these essential elements."¹⁴

LEAD SCAVENGERS

When lead additives were first discovered to improve gasoline octane quality, they were also found to cause many problems associated with vehicles, especially significant deposits in the combustion chamber and on spark plugs, causing durability problems. To relieve this, lead scavengers were added with lead to gasoline to encourage greater volatility in lead combustion by-products so they would be exhausted from the vehicle. These scavengers are used today in leaded gasoline. Ultimately, such additives are largely emitted from vehicles. This is important because these lead scavengers, most notably ethylene dibromide, have been found to be carcinogenic in animals, and have been identified as potential human carcinogens by the National Cancer Institute.¹⁵ Their removal, along with the removal of lead, should result in significant health benefits.

CARBON MONOXIDE

Carbon monoxide (CO)—an odorless, invisible gas, created when fuels containing carbon are burned incompletely—poses a serious threat to human health. Persons afflicted with heart disease and carrying fetuses are especially at risk. Because hemoglobin's affinity for CO is 200 times greater than for oxygen, CO hinders oxygen transport from blood into tissues. Therefore, more blood must be pumped to deliver the same amount of oxygen. Numerous studies in humans and animals have demonstrated that individuals with weak hearts are placed under additional strain by the presence of excess CO in the blood. In particular, clinical health studies have shown

a decrease in time to onset of angina pain in those individuals suffering from angina pectoris and exposed to elevated levels of ambient CO.¹⁶

NITROGEN OXIDES

As a class of compounds, nitrogen oxides (NO_x) are linked to a host of environmental concerns that negatively impact human health and welfare. Nitrogen dioxide (NO_2) has been linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics, and decreased pulmonary function.^{17, 18} It has been shown that even short-term NO_2 exposure results in a wide range of respiratory problems in school children—coughs, runny noses, and sore throats are among the most common.¹⁹ A French study by Dr. Orehek has shown that asthmatics are especially sensitive to even one-hour exposures.²⁰ A small group of asthmatics were initially exposed to carbachol, a broncho-constrictor representative of urban pollen, and then to NO_2 ; some participants experienced adverse effects, such as increased airway resistance, at levels as low as 0.1 parts per million for 1 hour.

NO_x also participates in the formation of the family of compounds known as photochemical oxidants, and in acid deposition. Finally, as a result of secondary transformations in the atmosphere, NO_x emissions are converted to nitrates, thereby increasing the accumulation of particulates in the air.²¹

PHOTOCHEMICAL OXIDANTS

The most widespread air pollution problem in temperate climates is ozone, a photochemical oxidant resulting from the reaction of NO_x and hydrocarbons in the presence of sunlight. Motor vehicles are a major source of both of these precursor pollutants. Ozone causes eye irritation, coughing, chest discomfort, headache, upper respiratory illness, increased asthma attacks, and reduced pulmonary function.²²

USEPA has recently proposed to lower the current ozone air quality standard from 0.12 parts per million (ppm) to 0.08 ppm.²³ Furthermore, attainment of the standard would no longer be based upon 1-hour averages, but instead on 8-hour averages. The proposed revised standard would provide protection for children and other populations vulnerable to a wide range of ozone-induced health effects, including decreased lung function (primarily in children active outdoors), increased respiratory symptoms (particularly in highly sensitive individuals), hospital admissions and emergency room visits for respiratory causes (among children and adults with pre-existing respiratory diseases such as asthma), and inflammation and possible long-term damage of the lungs.

It has also been demonstrated in numerous studies that photochemical pollutants seriously impair certain crops' growth. For example, the Congressional Research Service (U.S. Library of Congress) found that "[T]he short-run or immediate impacts of ozone are evident in annual crop yield decreases estimated at US\$1.9 to US\$4.3 billion."²⁴

PARTICULATES

A series of studies released in the last few years indicate that particulates (PM) may be the most serious urban air pollution problem. By correlating daily weather, air pollutants, and mortality in six U.S. cities, scientists have discovered that non-accidental death rates tend to rise and fall in near lockstep with daily PM levels—but not with other pollutants.²⁵ Because the correlation held up at even very low levels—in one city at just 23 percent of the federal PM limit—these analyses suggested to the researchers that as many as 60,000 U.S. residents per year may die from breathing particulates at or below legally allowed levels.²⁶

More recently, another study has emerged showing a strong link between particulate air pollution and mortality.²⁷ The study is distinctive in that it used a prospective cohort design that allowed for direct control of other individual risk factors such as cigarette smoking or diet. In

addition, the study was larger and represented a greater geographic area than any previous study.

Air pollution data from 151 U.S. metropolitan areas were linked with individual risk factors in 552,138 adults who resided in these areas when were enrolled in this 1982 study. Deaths were ascertained through 1989. Sulfates and fine particulate air pollution were associated with a difference of approximately 15–17 percent between mortality risks in the most polluted cities, and in the least polluted cities. Even in cities meeting U.S. Federal Clean Air standards, the risk of death is 2–8 percent higher than in the cleanest cities.

Certain particles appear to be especially hazardous. For example, diesel particles, because of their chemical composition and extremely small size, have raised special health and environmental concerns. Diesel PM consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and sulfates. In older diesels, soot was typically 40–80 percent of the total PM. Newer in-cylinder emissions controls have reduced the soot contribution to particulate emissions from modern emissions-controlled engines considerably. However, much of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction (SOF) of the particulate matter. The SOF is derived from lubricating oil, unburned fuel, and compounds formed during combustion. The relative importance of each of these sources varies from engine to engine.

The International Agency For Research on Cancer conducted a comprehensive assessment of available health information on diesel PM in June 1988, and concluded that diesel PM is probably carcinogenic to humans.²⁸

Other studies conducted at the Fraunhofer Institute in Germany have suggested that the diesel particle itself, stripped of organic and other surface materials, may also be carcinogenic. Studies under the auspices of the Health Effects Institute (HEI), a jointly funded industry-government program, recently verified this conclusion. An HEI

study reported that, “[R]esults, and recent findings from other laboratories, suggest that (1) the small respirable soot particles in diesel exhaust are primarily responsible for lung cancer developing in rats exposed to high concentrations of diesel emissions, and (2) at high particle concentrations, the mutagenic compounds adsorbed onto the soot play a lesser role, if any, in tumor development in this species.”²⁹ This is quite significant, as it indicates that it is important to control the particles themselves, not just the organic material sitting on the surface of the carbon.

In a subsequent analysis, HEI raised questions about this conclusion. The authors argue that because the rats were exposed to very high concentrations over their full lifetimes, the observed effects are more likely the result of the impairment of the rat’s ability to clear particles from its lungs, leading to inflammation and rapid cell proliferation. The researchers noted that similar effects did not occur in hamsters, and results with mice were mixed.³⁰

While further studies are carried out to determine which diesel particle elements are most hazardous, the prudent course of action would seem to be to reduce both the organics and the particulate mass.

To put the concerns with diesel NO_x and PM into perspective, one recent study attempted to quantify the health benefits associated with reducing diesel PM and NO_x .³¹ Based on a careful review of the available health information, the authors concluded that reducing one gram per mile of PM or NO_x over a 100,000-mile vehicle lifetime would produce benefits of US\$11,432 and US\$1,175, respectively. Focusing specifically on Los Angeles’ 1992 heavy-duty vehicle fleet, the authors conclude that a 50 percent reduction in NO_x and PM_{10} emissions would be worth US\$9,200 and US\$13,500 per vehicle. A 90 percent reduction would have a value of US\$16,600 and US\$24,300 per vehicle respectively. It is important to emphasize that these amounts reflect only the health benefits. Studies indicate that the economic benefits of reduced soiling and improved visibility are also significant.

PHYSICS AND CHEMISTRY OF PARTICULATE MATTER

Atmospheric particles originate from a variety of sources and possess a range of morphological, chemical, physical, and thermodynamic properties. Examples include combustion-generated particles such as diesel soot or fly ash, photochemically produced particles such as those found in urban haze, salt particles formed from sea spray, and soil-like particles from resuspended dust. Particles are liquid or solid; others contain a solid core surrounded by liquid. Atmospheric particles contain inorganic ions and elements, elemental carbon, organic compounds, and crustal compounds. Some atmospheric particles are hygroscopic and contain particle-bound water. The organic fraction is especially complex. Hundreds of organic compounds have been identified in atmospheric aerosols, including alkanes, alkanoids and carboxylic acids, polycyclic aromatic hydrocarbons, and nitrated organic compounds.³²

Particle diameters span more than four orders of magnitude—from a few nanometers to one hundred micrometers. Combustion-generated particles, such as those from power generation, automobiles, and tobacco smoke, can be as small as 0.01 micrometers or as large as 1 micrometer. Atmospheric particles produced by photochemical processes range in diameter from 0.05 micrometers to 2 micrometers. Fly ash produced by coal combustion ranges from 0.1 micrometers to 50 micrometers or more. Wind-blown dust, pollens, plant fragments, and cement dust are generally above 2 micrometers in diameter.

Recent measurements of the size distributions of primary particles confirm USEPA conclusions that most fugitive dust emissions are particles larger than 2.5 micrometers, and that most emissions from combustion sources are in sizes smaller than 2.5 micrometers. As illustrated in figure A.1, diesel truck emissions are almost all less than 1.0 micrometer in size; particles in this size range are especially hazardous when inhaled as they are able to penetrate to the deepest part of the lung, where the critical gas exchange takes place.

SOURCES OF SUSPENDED PARTICLES

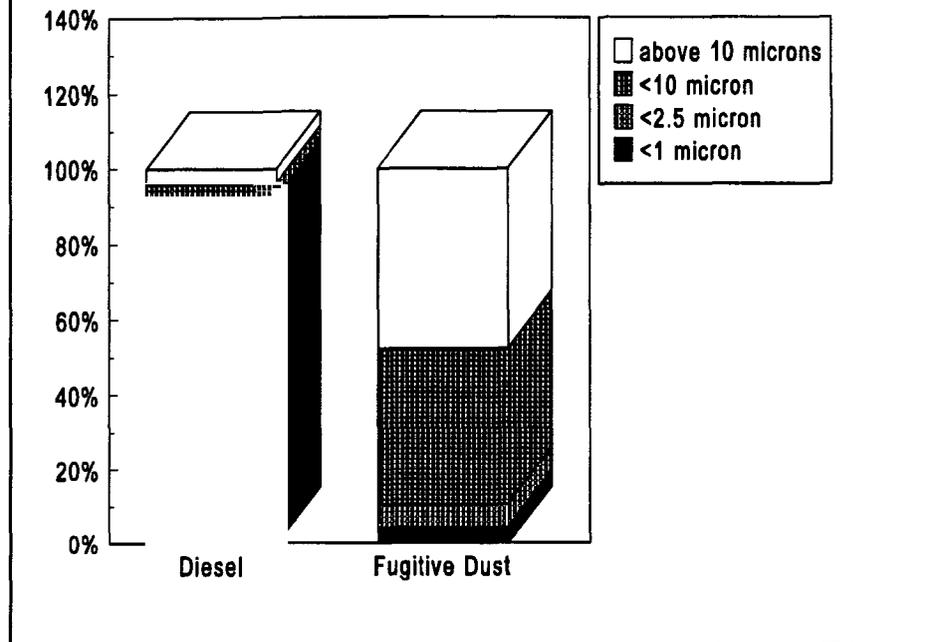
The ambient atmosphere contains both primary and secondary particles; the former are emitted directly by sources, and the latter are formed from gases (SO_2 , NO_x , NH_3 , VOCs). Fugitive dust is a primary pollutant. Major sources of particle emissions are classified as major point sources, mobile sources, and area sources; these are anthropogenic. Natural sources also contribute to ambient concentrations.

Fugitive dust is a major PM_{10} contributor at nearly all sampling sites, although the average fugitive dust source contribution is highly variable between sampling sites in the same areas, and is also highly variable between seasons.

Primary motor vehicle exhaust in the United States represents as much as 40 percent of average PM_{10} at many sampling sites. Vegetation burning outdoors and residential wood burning are significant sources in residential areas. Fugitive dust from paved and unpaved roads, agricultural operations, construction, and soil erosion constitute about 90 percent of nationwide primary emissions in most countries. Fugitive dust consists of geological material that is suspended into the atmosphere by natural wind and anthropogenic activities from sources such as paved and unpaved roads, construction and demolition of buildings and roads, storage piles, wind erosion, and agricultural tilling.

Mobile sources are major emitters of primary particles, NO_x , and VOCs. They are also minor emitters of SO_2 and ammonia. On-road gasoline-

Figure A.1: Size Distribution of Typical Particles



and diesel-fueled motor vehicle engines are the primary source of mobile source emissions in most countries, and consequently, emissions estimation methods are most highly developed for these vehicles. Motor vehicle exhaust contains high concentrations of organic and elemental carbon, but their ratios are very different from those found in wood combustion, elemental carbon being nearly equal to the organic carbon abundance.

OTHER TOXICS

The 1990 Clean Air Act directed USEPA to complete a study of toxic air emissions associated with motor vehicles and motor vehicle fuels. The study found that the aggregate risk in the United States is 720 cancer cases. Gasoline and diesel PM, which are considered to represent motor vehicle polycyclic organic matter (POM), are roughly equal contributors to the risk. The combined risk from gasoline and diesel PM was 16–28 percent of the total, depending on the year examined. Benzene is responsible for roughly 10 percent of the total for all

years. The aldehydes, predominately formaldehyde, were responsible for roughly 4 percent of the total for all years.

A variety of studies have found that in metropolitan areas mobile sources are possibly the most important air pollution source category, in terms of contributions to health risks. For example, according to USEPA, mobile sources are responsible for almost 60 percent of air pollution-related cancer cases in the United States per year.

Table A.1: Summary of WHO-Recommended Guidelines

Compound	Guideline Value	Averaging Time
Ozone*	120 g/m ³ (0.06 ppm)	8 hours
Nitrogen Dioxide	200 g/m ³ (0.11 ppm)	1 hour
Nitrogen Dioxide	40-50 g/m ³ (0.021-0.026 ppm)	Annual
Carbon Monoxide	100 mg/m ³	15 minutes
Carbon Monoxide	60 mg/m ³	30 minutes
Carbon Monoxide	30 mg/m ³	1 hour
Carbon Monoxide	10 mg/m ³	8 hours
Particulate Matter	**	

* Resulting from the photochemical reaction between hydrocarbons and nitrogen oxides.

** No guideline values were set for particulate matter because there is no evident threshold for effects on morbidity and mortality.

CONCLUSIONS REGARDING ADVERSE HEALTH EFFECTS

Vehicle emissions of CO, HC, NO_x, and fine PM result in a variety of adverse effects on health and the environment. Focusing solely on the health consequences of these pollutants, the World Health Organization (WHO) recently published revised air quality guidelines for Europe, which are summarized in table A.1.

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APPENDIX B: CONTROLS ON GASOLINE-FUELED VEHICLES

Over the last decade, great progress has been achieved in the development of control technologies that have dramatically reduced gasoline-fueled vehicle emissions, and the many adverse health and environmental effects of these emissions. However, to maximize these benefits and utilize the best available technology—the emissions catalyst—it is necessary to fuel catalyst-equipped vehicles exclusively with unleaded gasoline, since lead poisons converter systems. The following section reviews the technologies available to reduce gasoline vehicle emissions, and the important role that catalysts play in a successful long-term clean fuel strategy.

Before emissions controls were mandated, engine crankcase fumes were vented directly into the atmosphere. Crankcase emissions controls involved closing the crankcase vent port, and were introduced in new automobiles in the early 1960s. Controlling these emissions is no longer considered a significant technical issue.

Evaporative hydrocarbon (HC) emissions result from fuel evaporation in the carburetor float bowl and fuel evaporation in the gas tank. Controlling these emissions generally requires feeding the HC vapors back into the engine to be burned with the rest of the fuel. When the engine is not operating, vapors are stored either in the engine crankcase, or in charcoal canisters which absorb these emissions to be burned off when the engine is started.

The most difficult emissions control problem is that of vehicle exhaust emissions. Fortunately, progress has been made during the last decade in developing control technologies that can dramatically reduce exhaust pollutants. These technolo-

gies involve the physics of combustion, changes in engine design, and exhaust treatment devices.

COMBUSTION AND EMISSIONS

Hydrocarbon (HC) emissions include thousands of chemical compounds, generally resulting from incomplete fuel combustion. The amounts emitted are related to the air/fuel mixture inducted, peak temperatures and pressures in each cylinder (whether lead is added to the gasoline or not), and hard-to-define factors including combustion chamber geometry.

Nitrogen oxides (NO_x) are generally formed during conditions of high temperature and pressure, and excess air (to supply oxygen). Peak temperatures and pressures are affected by a number of engine design and operating variables as well as the concentrations of NO_x in the exhaust.

Carbon monoxide (CO) results from incomplete combustion of carbon contained in the fuel. Its concentration is generally governed by complex stoichiometry and equilibrium considerations. The only major engine design or operating variable that seems to affect its concentration is the air/fuel mixture: the leaner the mixture or the more air per unit of fuel, the lower the CO emissions rate.

Lead compounds (and their associated scavengers) are emitted by an automobile almost directly in proportion to the amount of fuel used by a vehicle, and the concentration of lead in the fuel.

ENGINE DESIGN PARAMETERS

Certain engine design parameters can induce significant changes in emissions. Most notable among these are the air/fuel ratio and mixture preparation, ignition timing, and combustion chamber design and compression ratio.

Air/Fuel Ratio and Mixture Preparation

The air/fuel ratio has a significant effect on all three major pollutants (CO, HC, and NO_x) from gasoline engines. In fact, engine-out CO emissions are almost totally dependent on the air/fuel ratio, while HC and NO_x emissions rates are strongly influenced, depending on other engine design parameters. CO emissions can be dramatically reduced by increasing the air/fuel ratio to the lean side of stoichiometric. HC emissions can also be reduced significantly by increasing the air/fuel ratio until flame speed becomes so slow that pockets of unburned fuel are exhausted before full combustion occurs or, in extreme cases, if misfire occurs. Conversely, NO_x emissions increase as air/fuel mixtures are enleaned up to the point of maximum or peak thermal efficiency. Beyond this point, further enleanment can result in lower NO_x emissions rates.

Ignition Timing

Ignition timing is the second most important engine control variable affecting "engine-out" HC and NO_x from modern engines. When timing is optimized for fuel economy and performance, HC and NO_x emissions are also relatively high (actual values depending, of course, on other engine design variables). As ignition timing is delayed (retarded), peak combustion temperatures tend to be reduced, thereby lowering NO_x and peak thermal efficiency. By allowing combustion to continue after the exhaust port is opened (resulting in higher exhaust temperatures), oxidation of unburned hydrocarbons is greater, and overall hydrocarbon emissions are reduced.

Compression Ratio and Combustion Chambers

According to the fundamental laws of thermodynamics, increases in compression ratio lead to improved thermal efficiency, and concurrently, increased specific power and reduced specific fuel consumption. In actual applications, increases in compression ratios tend to be limited by available fuel octane quality. Over time, a balance is struck between increased fuel octane values (through refining modifications and fuel modifications, such as the addition of tetraethyl lead to gasoline), and higher vehicle compression ratios.

Compression ratios can be linked to combustion chamber shapes, and in certain combinations these parameters can have a significant impact on emissions. Higher surface to volume ratios will increase the available quench zone and lead to higher HC emissions; conversely, more compact shapes, such as hemispherical or bent roof chambers, reduce heat loss and increase maximum temperatures. This tends to increase the formation of NO_x while reducing HC. Furthermore, combustion chamber material, and size and spark plug location can influence emissions. In general, because of its higher thermal conductivity, aluminum engine heads lead to lower combustion temperatures, and therefore lower NO_x rates, although at the expense of increased HC emissions. Since the length of the flame path has a strong influence on engine detonation and fuel octane requirement, larger combustion chambers that can lower HC emissions tend to be used only with lower compression ratios.

EMISSIONS CONTROL TECHNOLOGIES

Tighter emissions standards have required that more specific attention be given to the treatment of vehicle exhaust emissions. Commonly used technologies to control exhaust emissions include recirculation of exhaust gases, electronic control

of engine performance, exhaust after-treatment devices, and advanced combustion techniques.

State-of-the-art engine modification alone cannot reduce emissions to the same extent as can a three-way catalyst. Compared to a carburetted engine, an electronically controlled engine equipped with a 3-way catalyst can reduce CO emissions from a mean rate of 7.5 grams per kilometer to 1.5 grams per kilometer; HC emissions from 1.5 grams per kilometer to 0.25 grams per kilometer; and NO_x from 2.0 grams per kilometer to 0.25 grams per kilometer. Electronic fuel injection and ignition systems (EFI) without a catalytic converter are effective in reducing CO and HC emissions but have only a minor impact on NO_x emissions.¹

Exhaust Gas Recirculation

Recirculating a portion of the exhaust gas back into the incoming air/fuel mixture is frequently used as a technique to lower NO_x . The dilution of the incoming charge reduces peak cycle temperature by slowing flame speed and absorbing some combustion heat.

Charge dilution of homogeneous-charge engines by excess air and/or by exhaust gas recirculation (EGR) has been used for many years. The use of excess air alone results in relatively small NO_x reductions of about 35–40 percent. When EGR is incorporated, substantially higher NO_x reductions have been demonstrated. However, excessive dilution can result in increased HC emissions, driveability problems, or fuel economy losses.

Fuel consumption can be modified when EGR is utilized. Brake-specific fuel consumption and exhaust temperature decrease with increasing EGR, because dilution with EGR decreases pumping work and heat transfer, and increases the ratio of specific heats of the burned gases. Improvements in mixture preparation, induction systems, and ignition systems can increase dilution tolerance. The latest technique for improving dilution tolerance is to increase the air-fuel

charge's burn rate or flame speed. Dilution can then be increased until the burn rate again becomes limiting. Several techniques have been used to increase burn rate including increased "swirl" and "squish," shorter flame paths, and multiple ignition sources.

Electronics

With so many interrelated engine design and operating variables playing an increasingly important role in the modern engine, the control system has become increasingly important. Spark timing modifications must be closely coordinated with air/fuel ratio changes and amount of EGR, lest significant fuel economy or performance penalties result from emissions reductions, or NO_x emissions increase as CO decreases. In addition, controls that can be more selective depending on engine load or speed have been found beneficial in preventing adverse impacts.

To meet these requirements, electronics have begun to replace more traditional mechanical controls. The conventional combination of carburetor and distributed ignition systems can now be replaced by electronic fuel injection (EFI) and ignition to provide more precise control.² Further, electronic ignition timing control has been shown to optimize timing under all engine conditions, and has the added advantage of reduced maintenance and improved durability, compared to mechanical systems. When both ignition timing and EGR are electronically controlled, NO_x emissions can be reduced with no fuel economy penalty, and in some cases, with an improvement.

Exhaust After-Treatment Devices

Emissions catalysts and thermal reactors, generically known as exhaust after-treatment devices, were developed in order to achieve a quantum reduction in exhaust emissions beyond those attainable through engine design modifications. The catalyst comprises a ceramic support, a washcoat (usually aluminum oxide) to provide a

very large surface area, and a surface layer of precious metals (platinum, rhodium, and palladium are the most commonly used) to perform the catalytic function. The catalyst is housed in a metal container forming part of the vehicle exhaust system. For effective operation, the catalyst temperature must exceed the light-off value (about 3000 °C), which takes 1–3 minutes in typical urban driving conditions.³ The cost of a catalytic converter and its accompanying equipment is about US\$250–750 per automobile (1981 prices), equivalent to a 4–20 percent increase in vehicle cost.⁴ Over the life of a vehicle, these devices can reduce HC emissions by an average of 87 percent, CO by 85 percent, and NO_x by 62 percent.⁵

An oxidation catalyst is a device placed on the tailpipe of a car. If the chemistry and thermodynamics are properly maintained, the device will oxidize almost all the HC and CO in the exhaust stream to carbon dioxide and water vapor. Starting in 1975, oxidation catalysts have been placed in more than 80 percent of all new cars sold in the United States. In 1981, they have been placed on 100 percent of new cars. A major impediment to the use of catalysts is lead in gasoline. Catalyst systems are destroyed by the lead in vehicle exhaust. A unique advantage of catalysts is their ability to selectively eliminate some of the more harmful compounds in vehicle exhaust such as aldehydes, reactive hydrocarbons, and polynuclear hydrocarbons.

Three-way catalysts are able to lower HC, CO and NO_x levels simultaneously. Volvo first introduced them in the United States in 1977. They became widely used when the U.S. NO_x standard became more stringent (1.0 grams per mile) in 1981. For three-way catalysts to work effectively, it is necessary to control air/fuel mixtures much more precisely than is needed for oxidation catalyst systems. As a result, three-way systems have indirectly fostered improved air/fuel management systems such as advanced carburetors, throttle body fuel injection, and electronic controls. Three-way catalyst systems are also

sensitive to the use of leaded gasoline. Even an occasional tank of leaded gasoline will have a small but permanent effect on the level of emitted pollutants.

Thermal reactors are well-insulated vessels with internal baffling to allow several passes of the exhaust gas to maintain high temperatures and extend the residence time, and therefore promote oxidation of CO and HC emitted from the engine. To maintain high temperatures, they are often used in conjunction with exhaust port liners, which reduce heat losses. In spite of this, a major problem with these systems is the difficulty in maintaining exhaust temperatures high enough to promote combustion. Measures to increase exhaust temperatures such as retarded ignition, richer air/fuel ratios, or valve timing delays result in increased fuel consumption. Because of these problems, thermal reactors have gradually disappeared.

Lean-Burn

At one point, it was believed that combustion advances, especially lean-burn, might ultimately allow the catalyst to be eliminated. Recent experience, however, indicates that low HC and NO_x levels are not attainable across the range of normal driving conditions through the use of advanced combustion technology alone. At least an oxidation catalyst is needed to control HC emissions. Also, under higher speeds and higher load driving modes, such as those reflected in the recently established European extra urban driving cycle, supplemental NO_x control may also be needed. Recent European studies of high-speed driving conditions demonstrate that three-way catalysts are necessary to minimize NO_x emissions. In addition, concerns regarding toxic pollution are increasing, and lean-burn engines do not appear to be as effective as conventional catalyst-equipped engines in lowering polynuclear organics and other noxious compounds from motor vehicle exhausts, unless they are also equipped with catalytic converters.

EMISSIONS CONTROL AND ENERGY CONSERVATION

Today there are many technologies to improve fuel economy and reduce significant exhaust emissions, such as advanced air/fuel management systems including fuel injection, spark timing electronic controls, advanced choke systems, and improved transmissions. In fact, some advances were made as a direct result of increasingly tighter emissions control requirements. Furthermore, in the absence of tightening emissions requirements these advanced technologies almost certainly would not have been placed in automobiles. Once the technologies were introduced, fuel economy often improved faster than when emissions requirements were less stringent.

Lead is added to gasoline because it is an expensive way to increase octane values for improved vehicle fuel efficiency. In fact, a halt to adding lead in gasoline entails a small (less than 1 percent in the United States) fuel penalty at the refinery. However, the greatest potential impact, and the one that has generated the most serious

debate, is the impact on vehicle fuel efficiency—does it improve or deteriorate?

In Europe, North America, and the Pacific Rim, vehicle technology is being pushed harder and harder to achieve low pollution levels, and common elements are emerging. In every case the least-polluting vehicles are equipped with catalytic converters. As these systems are destroyed by lead and by phosphorus in most engine oils, they inevitably foster the introduction of unleaded gasoline and cleaner engine oils, resulting in overall reductions in lead pollution. Further, to optimize the effectiveness of these systems, better air/fuel and spark management systems have evolved, generating a much greater use of both electronics and fuel injection. In turn, these advances increase the prospects of better fuel efficiency and lower CO₂ emissions.

COST OF EXHAUST EMISSIONS CONTROLS

Implementing tighter emissions standards has three cost implications:

- Increased vehicle costs, including additional or more advanced components;
- Increased or reduced vehicle maintenance costs; and
- Greater or lesser amounts of fuel consumed if emissions control measures affect fuel consumption one way or the other.

Estimated increases in the cost of vehicles and changes in fuel consumption for various low-emissions engines and exhaust treatment configurations are given in table B.1.⁶

In the United States, USEPA developed a cost model to determine estimates of the initial cost paid by consumers to comply with U.S. emissions standards. The cost estimates were based on an analysis of the retail price equivalent of each component in the emissions control system component used in gasoline-fueled vehicles. The list of emissions control components on each car was obtained from the Application for Certification submitted to USEPA by automobile manufacturers. Prices and price estimates were ob-

Box B.1: U.S. Fuel Efficiency Under Emissions Standards (-1987)

In the United States, improved emissions standards have coincided with improvements in fuel economy. A sales-weighted fleet average of 14.9 miles per gallon in 1967 increased to 27.3 miles per gallon in 1987—an increase of 83 percent. Correcting for vehicle weight reductions, the improvements, compared with pre-controlled cars were about 47 percent. The introduction of unleaded fuel and catalytic converters in 1975 coincided with substantial fuel economy gains. At a minimum, this demonstrates that tight emissions standards are not an impediment to fuel economy gains. Because some technologies such as electronic controls, advanced spark management systems, or advanced air-fuel management systems are beneficial for both emissions reductions and improved fuel efficiency, encouraging use of these systems in response to tight emissions standards may actually have stimulated some advances in fuel economy.

Table B.1: The Cost to Consumers of Various Emissions Control Technologies:

Technologies	Price Increase (percent)	Fuel Consumption Increase (percent)
Lean-burn engine with carburetor and conventional ignition	1.0	-2
Pulsair and EGR	4.5	+3
Lean-burn engine with carburetor and programmed ignition	2.0	+1
Recalibrated conventional engine with EFI	8.0	+2
Lean-burn engine and EFI	9.0	-7
Lean-burn engine oxidation catalyst	4.5	-3
Open loop 3-way catalyst carburetor	4.1	+2
Lean-burn engine-closed loop, EFI variable intake system-oxidation catalyst	15.0	-7
Closed loop-EFI-3-way catalyst	13.0	+3

Baseline: small vehicle, 1.4 litre conventional carburetor engine meeting ECE 15/04 standard.

Recognizing that there is no universal consensus regarding the cost and fuel economy impacts of emissions regulations, it would still be fair to say that technology exists which can lower emissions at a cost of approximately 3–5 percent of the overall cost of a vehicle with no pollution controls, and with improved fuel economy.

TECHNOLOGICAL ADVANCES ON THE HORIZON

Vehicle emissions reduction technology is continually evolving.

tained from three sources: (i) a study conducted for USEPA; (ii) a price survey of dealer parts departments; and (iii) direct request to the manufacturers for parts price information. Based on the above sources, new automobile price increases resulting from tighter U.S. emissions standards were estimated (table B.2). All emissions standards have been converted to the U.S. 1975 test procedure (CV5-75) along with the U.S. compliance program.

An international workgroup has been formed under the auspices of the Convention on Long Range Transboundary Air Pollution to discuss methods for researching VOC emissions and control strategies. As part of the development of a UN ECE protocol to control these emissions, a technical annex (dealing with mobile sources) was drafted in Switzerland on April 6, 1990. The major conclusion was that closed loop three-way catalyst technology is cleaner and more efficient than either engine modifications or lean-burn settings with open loop catalysts.

Future control elements will include lower trace lead levels in unleaded gasoline, more advanced emissions control components, more durable catalysts, better air fuel management systems, and electronics. California, still plagued by severe smog conditions in Los Angeles, continues its worldwide leadership in extending pollution control requirements.

Technological improvements for controlling HC and CO. The level of tailpipe HC emissions from modern vehicles is primarily a function of engine-out emissions, and the catalyst's overall conversion efficiency, both of which are highly dependent the fuel and ignition systems functioning properly. A fairly comprehensive system which tackles this problem has evolved. A significant portion of HC and CO emissions are generated during cold starts, when the fuel system is operating in a rich mode and the catalyst has not yet reached its light-off temperature. There are many feasible technological improvements on the horizon that are expected to control HC and CO

emissions more stringently, not only reducing emissions levels in new vehicles, but also emissions for vehicles in service.

Increased use of fuel injection. The trend toward increased use of fuel injection has several distinct advantages over carburetion as a fuel control system, including more precise control of fuel metering, better compatibility with digital electronics, better fuel economy, and better cold-start function. Fuel metering precision is important in maintaining a stoichiometric air/fuel ratio for efficient three-way catalyst operation. Efficient catalyst operation, in turn, reduces the need for dual-bed catalysts, air injection, and EGR. Better driveability from fuel injection has been a motivation to convert engines from carburetion to fuel injection. In fact, it has been projected that the percentage of new California light-duty vehicles with fuel-injection will reach 95 percent by the early 1990's, with 70 percent being multi-point. Because of fuel injection systems' inherently better fuel control, this trend is highly consistent with more stringent emissions standards.

Fuel injection's compatibility with onboard electronic controls enhances fuel metering pre-

Table B.2: U.S. Automobile Emissions Standards (grams per mile) and Estimated Additional Cost (1968-96)^{7,8}

Model Year	HC/CO/NOx (grams/mile)	Initial cost increase (US\$ 1981)
1968-69	5.9/50.8/N.R.	30
1970-71	3.9/33.3/N.R.	50
1972	3.0/28.8/N.R.	70
1973-74	3.0/28.0/3.1	100
1975-76	1.5/15.0/3.1	150
1977-79	1.5/15.0/2.0	175
1980	0.41/7.0/2.0	225
1981	0.41/3.4/1.0	350
1990 (proposed legislation)	0.25/3.4/0.4 (by 1995/96) 0.125/3.4/0.2 (by 2003)	n.a. n.a.

N. R. = not required.

n. a. = not available.

^{1/} OECD [1988a]. Transport and Environment, Paris.

USEPA [1988]. Mobile Source Emission Standards Summary. Office of Air and Radiation, United States Environment Protection Agency, Washington, D.C.

Table B.3: Conclusion of UN ECE Protocol (1990)

Technology Option	Emission Level	Cost	Fuel Consumption
Uncontrolled	400		<100
Engine Modifications	100	Base	100
Lean Setting w/ox. Cat	50	150-200	100
Closed Loop TWC	10	250-400	95
Advanced Closed Loop	6	350-600	90

cision, and also gives manufacturers the ability to integrate fuel and emissions control systems into an overall engine management system. This permits early detection and diagnosis of malfunctions, automatic compensation for altitude, and to some degree, adjustments for normal wear. Carburetor choke valves, long considered a tar-

get for maladjustment and tampering, are replaced by more reliable cold-start enrichment systems in fuel-injected vehicles.

Closed-loop feedback systems are critical to maintaining good fuel control. However, when they fail, emissions can increase significantly. In fact, CARB in-use surveillance data show that component failure in a closed-loop system frequently is associated with high emissions. CARB's new onboard diagnostics requirement will enable the system to alert the driver when something is wrong with the emissions control system and will help the mechanic to identify the malfunctioning component.

Improvements to the fuel control and ignition systems, such as increasing the ability to maintain a stoichiometric air/fuel ratio under all operating conditions, and minimizing the occurrence of spark plug misfire, will result in better overall catalyst conversion efficiency and less opportunity for catastrophic failure. These improvements, therefore, have a two-fold effect: (i) limiting the extra engine-out emissions that would be generated by malfunctions, and (ii) helping to keep the catalyst in good working condition.

Several alternative catalyst configurations will probably be used in the future to meet lower emissions standards. It is also likely that dual-bed catalysts will be phased out, and a warm-up catalyst (preceding the thermal warm-up catalyst or TWC) will be used for cold-start HC control. To avert thermal damage and lower the catalyst deterioration rate, this small catalyst will probably be bypassed at all times except during cold starts. Warm-up air injection could also be used with a single-bed TWC for cold-start HC control. As HC standards are lowered, preheated catalysts will probably become more important for many cars' pollution control systems.

TWO- AND THREE-WHEELED VEHICLES: SPECIAL CONCERNS

Two- and three-wheeled vehicles, especially motorcycles and auto-rickshaws, constitute a large

portion of motorized vehicles in developing countries, particularly in East and South Asia. While they are responsible for a relatively small fraction of total vehicle kilometers of travel (VKT) in most countries, they often contribute substantially to air pollution. This is especially true of motorcycles and auto-rickshaws with two-stroke engines running on a mixture of gasoline and lubricating oil. It has been estimated that uncontrolled motorcycles in industrialized countries emit 22 times as much HC and 10 times as much CO as automobiles controlled by U.S. 1978 levels.⁹ In Taiwan, HC emissions from two-stroke engine motorcycles were 13 times higher than emissions from new four-stroke motorcycles, and over 10 times higher than the emissions from in-use passenger cars. CO emissions from two-stroke motorcycle engines were similar to those from four-stroke engines.¹⁰

Technologies available to control emissions from two- and three-wheeled vehicles are similar to those available for other Otto cycle-powered engines. Reducing the amount of lubricating oil in the fuel is one possible approach. Refining the fairly simple carburetors used would significantly reduce HC, CO, and smoke emissions. Catalytic converters are also technologically feasible for these engines.¹¹

Many modern engines use a separated lubrication system which uses leaner fuel/oil ratios, and therefore reduces smoke. Since 1986 mopeds with catalysts have been available in Austria and Switzerland. In Taiwan motorcycles have been similarly equipped since 1992.

High smoke and unburned HCs from two-stroke engines are no longer technologically necessary. New technology promises to resolve these concerns. Direct cylinder electronic fuel injection, electronic computer control, and catalytic exhaust conversion are now common solutions. In addition, advanced two-stroke engines, such as those being developed by the U.S. firm Orbital indicate that these engines can be even cleaner and more fuel-efficient than four-stroke engines.

ADDITIONAL HEALTH BENEFITS FROM CATALYSTS

In addition to significant improvements in CO, HC, and NO_x emissions, emissions catalysts have several additional advantages.

Aldehydes are the most prevalent oxygenated organic species in gasoline engine exhausts. They tend to be highly photochemically reactive, and can cause serious eye irritation. One particular aldehyde—formaldehyde—has been found to be carcinogenic in animal tests. As illustrated below (table B.4), these compounds are effectively reduced by catalysts.

Reactive hydrocarbons. Exhaust HC standards are generally written in terms of total HCs. Certain of these HCs, such as methane, are of less environmental concern because they are chemically stable and tend not to produce photochemical smog.¹² However, since catalytic converters tend to selectively oxidize the more reactive HCs, a greater proportion of the HC species participating in the photochemical reactions leading to smog will be reduced by catalysts.

Polynuclear Aromatic Hydrocarbons (PAHs). Emissions from this class of HCs are of particular interest because of their direct carcinogenic effects on specific PAH compounds that have been detected in vehicle exhaust. Most notable among the PAHs is benzo(a)pyrene (BaP), a five-ring aromatic that has been shown in a number of experiments to be an animal carcinogen.

Listed below are BaP emissions data from passenger cars with various types of control technology (table B.5).

These data show that PAH emissions from gasoline-powered cars are reduced substantially by controls designed to reduce HC and CO, and that catalytic converters can almost eliminate them. In fact, the catalyst-equipped vehicles reduced BaP by over 99 percent from pre-controlled levels, and by about 96 percent from 1970 levels with first-generation emissions controls. There is every reason to conclude that the catalyst has similar impacts on other

multi-ring aromatics which are likely to be in gasoline vehicle exhaust. This was verified in a study conducted several years ago which measured various PAHs both with and without a catalyst. The data showed that PAHs are removed, often substantially, by catalysts (table B.6).

ENDNOTES

1. European Conference of Ministers of Transport. 1990. *Transport Policy and the Environment*. Organization of Economic Cooperation and Development: Paris.
2. European Conference of Ministers of Transport. 1990. *Transport Policy and the Environment*. Organization of Economic Cooperation and Development: Paris.
3. European Conference of Ministers of Transport. 1990. *Transport Policy and the Envi-*

Table B.4: Aldehyde Emissions from Passenger Cars

Vehicle Type	Aldehydes (grams per mile)
Average of 10 non-catalyst gasoline cars	0.141
Average of 3 catalyst gasoline cars	0.023

Table B.5: BaP Emissions from Passenger Cars with Different Emissions Controls

Vehicle Type	Emissions (Micrograms per mile)
Pre-emissions control	12.04
1968 emissions controls	2.77
1970 emissions controls	1.62
Catalyst-equipped	0.08

ronment. Organization of Economic Cooperation and Development: Paris.

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9. Organization of Economic Cooperation and Development. 1988. *Transport and Environment*, Paris.
10. Shen, S.-H., and K.-H. Huang, K.-H. 1989. "Taiwan Air Pollution Control Programme—

Table B.6: Polycyclic Aromatic Hydrocarbons With and Without a Catalyst

Polycyclic Aromatic/Hydrocarbon	Without Catalyst	With Catalyst	Percent Reduction
phenanthrene	1.85	0.16	91
anthracene	0.61	0.04	93
fluoranthrene	2.27	0.23	90
Phrene	2.91	1.50	48
perylene	1.21	0.40	67
benzo(a)pyrene	0.94	0.17	82
benzo(e)pyrene	2.76	0.41	85
dibenzopyrenes	0.28	0.23	18
coronene	0.41	0.27	34

Impact of and Control Strategies for Transportation-Induced Air Pollution." Bureau of Air Quality Protection and Noise Control, Environmental Protection Agency, Taiwan (China).

11. Organization of Economic Cooperation and Development. 1988. *Transport and Environment*, Paris.
12. While not a direct health concern in the urban environment, methane, one of the gases accumulating in the upper atmosphere, is an important potential greenhouse gas.

APPENDIX C: CONTROLS ON DIESEL-FUELED VEHICLES

Diesel engine emissions are determined by the characteristics of the combustion process within each cylinder. Primary engine parameters affecting diesel emissions are the fuel injection system, engine control system, air intake port and combustion chamber design, and the air charging system. Actions to reduce lubricating oil consumption can also impact hydrocarbon (HC) and particulate (PM) emissions. Beyond the engine itself, exhaust aftertreatment systems such as trap oxidizers and catalytic converters can play a significant role. Finally, modifications to conventional fuels, or alternative fuels, can substantially lower or raise emissions. The following sections will review the status of each technology area, as chapter 5 summarized the fuel impacts.

Except for PM, exhaust emissions (particularly HC and carbon monoxide) from diesel engines are quite low compared to gasoline engines; therefore much of the attention to diesel exhaust emissions has focused on PM and nitrogen oxide (NO_x) emissions. PM from diesel exhaust consists of soot, condensed HCs, sulfur-based compounds, and other oil-derived material. Smoke is the immediately visible portion of particulate emissions, and its opacity depends on the number and size of carbon particles present. The main cause of black smoke is poor maintenance of air filters or fuel injectors. Fuel quality can also affect smoke emissions, through fuel density, aromatic content, and certain distillation characteristics (T. J. Russell, 1989, ECMT, 1990).

Most the techniques for reducing PM and HC emissions from diesel engines also improve combustion efficiency and are fuel efficient. However, they result in higher NO_x exhausts.

Common approaches to emissions control require a series of diesel engine modifications including fuel injection, electronic engine controls, combustion chamber modifications, air handling characteristics, reduced oil consumption, turbocharging, injection retard, exhaust gas recirculation (EGR), and reduced heat rejection (ECMT 1990).

Efficient combustion through improved mixing of air and fuel results in lower HC and smoke emissions. Electronic control of fueling levels and timing, combined with high-pressure fuel injection systems, can be quite beneficial. Turbocharging increases NO_x emissions but reduces particulates. Charge cooling (cooling the intake air after the turbochargers) directly reduces NO_x emissions by reducing peak cycle temperatures and pressures. Injection retard is the most effective way of reducing NO_x emissions, but increases fuel consumption, smoke, and HC emissions, particularly under light loading. EGR can significantly reduce NO_x but may double particulate emissions. Effective control of lubricating oil through engine design prevents it from entering the engine piston rings, valve guides or turbochargers, and has been shown to reduce HC emissions by about 50 percent (ECMT 1990).

In order to achieve low levels of particulate emissions, manufacturers have also developed exhaust treatment devices that are added to clean up the exhaust after it leaves the engine. Several devices are being evaluated. One is a flow-through catalytic converter designed to operate on low-sulfur fuel. This may reduce the soluble organic fraction of particulates by as much as 90 percent, and may also reduce the carbon portion. Another,

probably more promising aftertreatment device, is the trap oxidizer control system, which has demonstrated particulate control efficiencies, in some instances, of over 90 percent.

ENGINE MODIFICATIONS

Air Motion and Combustion Chamber Design

The geometries of the combustion chamber and air intake port control the air motion in the diesel combustion chamber, and thus play an important role in air/fuel mixing and emissions. A number of different combustion chamber designs, corresponding to different basic combustion systems, are presently being used in heavy-duty diesel engines. This section outlines the basic combustion systems in use, their advantages and disadvantages, and the effects of changes in combustion chamber design and air motion on emissions.

Combustion Systems

Heavy-duty diesel engines use several different types of combustion systems. The most fundamental difference is between direct injection (DI) engines and indirect injection (IDI) engines. In an IDI engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main combustion chamber above the piston. In the more common DI engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. DI engines can be further divided into high-swirl and low-swirl.

Fuel/air mixing in the DI engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it enters. In high-swirl DI engines, a strong swirling motion is imparted to the air entering the combustion chamber by the design of the intake port. These engines typically use moderate to high injection pressures, and three to five spray holes per nozzle. Low-swirl engines rely primarily on the fuel injection process to supply the mixing. They typi-

cally have very high fuel injection pressures and six to nine spray holes per nozzle.

In the IDI engine, much of the fuel/air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the prechamber during combustion. These engines typically have better high-speed performance than DI engines, and can use cheaper fuel injection systems. Historically, IDI diesel engines have exhibited lower emissions levels than DI engines, but with recent developments in DI engine emissions controls this is no longer the case. Disadvantages of the IDI engine are the extra heat and frictional losses due to the prechamber, resulting in a 5–10 percent reduction in fuel efficiency compared to a DI engine.

A number of advanced, low-emitting, and fuel-efficient high swirl DI engines have recently been introduced; it appears that these engines will completely replace existing IDI designs.

Direct Injection Combustion Chamber Design

Changes in the engine combustion chamber and related areas demonstrate potential emissions reductions. Design changes to reduce the crevice volume in DI diesel cylinders increase the amount of air available in the combustion chamber. Changes in combustion chamber geometry—such as the use of a reentrant lip on the piston bowl—can markedly reduce emissions by improving air/fuel mixing and minimizing wall impingement by the fuel jet. Optimizing the intake port shape for best swirl characteristics has also yielded significant benefits. Several manufacturers are considering variable swirl intake ports to optimize swirl characteristics across a broader range of engine speeds.

The **crevice volume** is a part of the compression volume lying outside the combustion chamber. This includes the clearance between the top of the piston and the cylinder head, and the "top land"—the space between the side of the piston and the cylinder wall above the top compression

ring. The smaller the crevice volume, the larger the combustion chamber volume can be for a given compression ratio, effectively increasing the amount of air available for combustion.

The major approaches to reducing the crevice volume are to reduce the clearance between the piston and cylinder head through tighter production tolerances, and moving the top compression ring toward the top of the piston. This increases the top ring's working temperature, and poses mechanical design problems for the piston top and cooling system. These problems have been addressed through redesign and the use of more expensive materials. The higher piston ring temperature may also make additional demands on the oil.

In high-swirl DI engines, a re-entrant **combustion chamber shape** (where the lip of the combustion chamber protrudes beyond the walls of the bowl) provides a substantial improvement in performance and emissions over the previous straight-sided bowl designs. Researchers at AVL List (Austria) found that a re-entrant bowl gave a 20 percent reduction in PM emissions compared to those measured from a straight-sided bowl at the same compression ratio. NO_x emissions increased 3 percent, but the re-entrant bowl combustion chamber was found to be more tolerant of retarded injection timing than the straight-sided bowl.

Because of the superiority of the re-entrant bowl design in high-swirl engines, nearly all manufacturers of such engines are developing or already using this approach. Similar improvements in the performance of low-swirl DI engines may also be possible through modifications to combustion chamber geometry, but there is little agreement on what the optimal shape should be.

Optimal matching of the **intake air swirl** ratio with combustion chamber shape and other variables is critical for emissions control in high-swirl engines. The swirl ratio is the ratio of the rotational speed of the air charge in the cylinder to the rotational speed of the engine—determined by the design of the air intake port. The selection of a fixed swirl ratio involves some trade-offs between

low-speed and high-speed performance. At low speeds, a higher swirl ratio provides better mixing, permitting more fuel to be injected and thus greater torque output at the same smoke level. However, this can result in too high a swirl ratio at higher speeds while impairing the airflow to the cylinder. Too high a swirl ratio can also increase HC emissions, especially under light loads.

Attaining an optimal swirl ratio is more difficult in smaller engines because they experience a wider range of engine speeds than heavy engines. One solution to this problem is to vary the swirl ratio as a function of engine speed. A two-position variable swirl system has been developed and applied to some diesel engines in Japan, and is being considered for engines used in the United States as well. Test data using this system show a noticeable reduction in PM and NO_x emissions due to optimization of the swirl ratio at different speeds.

Fuel Injection

The fuel injection system is one of a diesel engine's most important components. It includes the process by which the fuel is transferred from the fuel tank to the engine, and the mechanism by which it is injected into the cylinders. The fuel injection's precision, characteristics, and timing determine the engine's power, fuel economy, and emissions characteristics.

The fuel injection system normally consists of a low-pressure pump transferring fuel from the tank to the engine; one or more high-pressure fuel pumps creating the pressure pulses that send the fuel into the cylinder; the injection nozzles where fuel is injected into the cylinder; and a governor and fuel metering system. These determine how much fuel is injected on each stroke, and thus the power output of the engine.

The major areas of concentration in fuel injection system development are increased injection pressure, increasingly flexible control of injection timing, and more precise governing of the fuel quantity injected. Systems offering electronic control of these quantities and fuel injec-

tion rate have been introduced. Some manufacturers are also pursuing technology to vary the rate of fuel injection over the injection period in order to reduce the amount of fuel burning in the premixed combustion phase. Reductions in NO_x and noise emissions, and maximum cylinder pressures have been demonstrated using this approach. Other changes have been made to the injection nozzles themselves to reduce or eliminate sac volume, and to optimize the nozzle hole size and shape, number of holes, and spray angle for minimum emissions.

Injection system types. Fuel injection systems used in heavy-duty diesel vehicles can be divided into two basic types. The most common type consists of a single fuel pump (typically mounted at the side of the engine) which is driven by gears from the crankshaft, and connected to individual injection nozzles at the top of each cylinder by special high-pressure fuel lines. These pump line nozzle injection systems can be further divided into two subclasses: **distributor** fuel pumps, in which a single pumping element is mechanically switched to connect to the high pressure fuel lines for each cylinder in turn; and **in line** pumps, having one pumping element per cylinder where each is connected to its own high pressure fuel line. The latter type is much more common in heavy-duty trucks.

The most common alternative to the pump line nozzle injection systems are systems using unit injectors, in which the individual fuel metering and pumping element for each cylinder is combined in the same unit with the injection nozzle at the top of the cylinder. The pumping elements in a unit injector system are generally driven by the engine camshaft.

Worldwide, many more engines are made with pump line nozzle injection systems than with unit injectors, due primarily to the higher cost of unit injector systems. Presently, three U.S. engine manufacturers (accounting for more than half of U.S. heavy-duty engine production) produce unit injector-equipped truck engines. Due to the absence of high pressure fuel lines, unit injectors are capable of higher injection pressures than

pump line nozzle systems. With improvements in electronic control, these systems offer better fuel economy at low emissions levels than the pump line nozzle systems. For this reason, many heavy-duty engine models sold in the United States were equipped with unit injectors for the 1991 model year.

Fuel injection pressure and injection rate.

High fuel injection pressures are desirable in order to improve fuel atomization and fuel/air mixing, and to offset the effects of retarded injection timing by increasing the injection rate. It is well established that higher injection pressures reduce PM and smoke emissions. High injection pressures are most important in low-swirl direct injection engines, since the fuel injection system is responsible for most of the fuel/air mixing in these systems. For this reason, low-swirl engines tend to use unit injector systems, that can achieve peak injection pressures in excess of 1,500 bar.

The injection pressures achievable in pump line nozzle fuel injection systems are limited by the mechanical strength of the pumps and fuel lines, as well as by pressure wave effects, to about 800 bar. Improvements in system design to minimize pressure wave effects, and increases in the size and mechanical strength of the lines and pumping elements have increased the injection pressures achievable in pump line nozzle systems substantially from those achievable a few years ago.

The pumping elements in all current fuel injection systems are driven through a fixed mechanical linkage from the engine crankshaft. This means that the pumping rate, and thus the injection pressure, is a strong function of engine speed. At high speeds the pumping element moves rapidly, and injection pressures and injection rates are high. Conversely, at lower speeds, the injection rate is proportionately lower, and injection pressure drops off rapidly. This poor atomization and mixing at low speeds can be a major cause of high smoke emissions during lugdown. Increasing the pumping rate to provide adequate pressure at low speeds is impractical, as it would exceed the system pressure limits at high speed.

A new type of in-line injection pump which provides a partial solution to this problem, has recently been developed. The cam driving the pumping elements in this pump has a non-uniform rise rate. This allows the pumping rate (at any given time) to be a function of the cam angle. By electronically adjusting a spill sleeve, it is possible to select the portion of the cam's rotation when fuel is injected, and vary the injection rate. Injection timing varies at the same time, but the system is designed for the desired injection rate and injection timing to correspond fairly well. Ishida and co-workers obtained a 25 percent reduction in PM emissions, and a 10 percent reduction in HC using this system with virtually no increase in NO_x . The same approach could easily be applied to a unit injector system using an electronically controlled spill valve.

Another approach to increasing injection pressure at low engine speeds is using electro-hydraulic actuators for injection instead of mechanically-driven pumping elements. Through appropriate design and control schemes, such systems can control and maintain fuel injection pressures almost independently of engine speed. A number of such systems have been described in the technical literature, but to date, such systems were introduced in the US in 1991.

Initial injection rate and premixed burning. Reducing the amount of fuel burned in the premixed combustion phase can significantly reduce total NO_x emissions. This can be achieved by reducing the initial rate of injection while keeping the subsequent rate of injection high to avoid high PM emissions due to late burning. This requires varying the rate of injection during the injection stroke. While this represents a difficult design problem for mechanical injection systems, it still should be possible using electro-hydraulic injectors. Another approach to the same end is split injection where a small amount of fuel is injected in a separate event ahead of the main fuel injection period.

Data published by a U.S. manufacturer show a marked beneficial effect from reducing the initial

rate of injection. Based on these data, it appears likely that a 30–40 percent reduction in NO_x emissions could be achieved through this technique without significant adverse impacts on fuel consumption or HC or PM emissions. As a side benefit, engine noise and maximum cylinder pressures (for a given power output) would also be reduced.

Low sac/sacless nozzles. The nozzle sac is a small internal space in the tip of the injection nozzle. The nozzle orifices open into the sac so that fuel flowing past the needle valve first enters the sac, then sprays out the orifices. The small amount of fuel remaining in the sac tends to burn or evaporate late in the combustion cycle, resulting in significant PM and HC emissions. The sac volume can be minimized or even eliminated by redesigning the injector nozzle. One manufacturer reported nearly a 30 percent reduction in PM emissions through elimination of the nozzle sac. It is also possible to retain some of the sac while designing the injector nozzle so that the tip of the needle valve covers the injection orifices when it is closed. This valve covers orifice (VCO) injector design is used in some production engines, and in many engines was developed to comply with 1991 U.S. emissions standards.

Engine Control Systems

Traditionally diesel engine control systems have been closely integrated with the fuel injection system, enabling the two systems to be discussed together. These earlier control systems (still used in most engines) are entirely mechanical. The last few years have seen the introduction of an increasing number of computerized electronic control systems for diesel engines. With the introduction of these systems, the scope of the engine control system has been greatly expanded.

Most current diesel engines still rely on **mechanical engine control systems**. The primary functions of these systems include basic fuel metering, engine speed governing, maximum power limitation, torque curve "shaping," limiting

smoke emissions during transient acceleration, and often, limited control of fuel injection timing. Engine speed governing is accomplished through a spring and flyweight system which progressively (and quickly) reduces the maximum fuel quantity as engine speed exceeds the rated value. The maximum fuel quantity itself is generally set through a simple mechanical stop on the rack controlling injection quantity. More sophisticated systems allow some "shaping" of the torque curve to change the maximum fuel quantity as a function of engine speed.

Acceleration smoke limiters are needed to prevent excessive black smoke emissions during transient acceleration of turbocharged engines. Most of these engines are designed to limit the maximum fuel quantity injected as a function of turbocharger boost, so that full engine power is developed only after the turbocharger comes up to speed.

Many pump line nozzle fuel injection systems incorporate mechanical injection timing controls. Since the injection pump is driven by a special shaft geared to the crankshaft, injection timing can be adjusted within a limited range by varying the phase angle between the two shafts using a sliding spline coupling. A mechanical or hydraulic linkage slides the coupling back and forth in response to engine speed or load signals.

In mechanical unit injector systems, the injectors are driven by a direct mechanical linkage from the camshaft, making it very difficult to vary the injection timing. Cummins, in its California engines, has introduced a mechanical timing control which operates by moving the injector cam followers back and forth with respect to the cam. Although effective in limiting light-load HC and PM emissions under stringent California NO_x standards, these systems have proven troublesome and unpopular among users.

Computerized electronic engine control systems have greatly increased the potential flexibility and precision of fuel metering and injection timing controls. In addition, whole new control functions have been made possible, such as road speed governing, alterations in control strategy during transients,

synchronous idlespeed control, and adaptive learning. This includes strategies to identify and compensate for the effects of wear, and component to component variation in the fuel injection system.

By continuously adjusting the fuel injection timing to match a stored "map" of optimal timing versus speed and load, an electronic timing control system can significantly improve on the NO_x/particulate and NO_x/fuel economy trade-offs possible with static or mechanically variable injection timing. Most electronic control systems also incorporate the functions of the engine governor and the transient smoke limiter. This helps to reduce excess particulate emissions due to mechanical friction and lag time during engine transients, while simultaneously improving engine performance. PM emissions reductions of up to 40 percent have been documented with this approach.

Other electronic control features such as cruise control, upshift indication, and communication with an electronically controlled transmission will also help to reduce fuel consumption, and will thus likely reduce in-use emissions. Since the effect of these technologies is to reduce the amount of engine work necessary per mile, rather than the amount of pollution per unit of work, their effects will not be reflected in dynamometer emissions test results.

Turbocharging and Intercooling

A turbocharger consists of a centrifugal air compressor feeding the intake manifold mounted on the same shaft as an exhaust gas turbine in the exhaust stream. By increasing the mass of air in the cylinder prior to compression, turbocharging correspondingly increases the amount of fuel that can be burned without excessive smoke, and thus increases the potential maximum power output. This also improves the engine's fuel efficiency. The process of compressing the air, however, raises its temperature, increasing the thermal load on critical engine components. By cooling the compressed air in an intercooler before it enters the cylinder, the adverse thermal effects can be reduced. In addition, the density of the air in-

creases, and allows an even greater mass of air to be confined within the cylinder, thus further increasing the maximum power potential.

Increasing the air mass in the cylinder and reducing its temperature can reduce both NO_x and PM emissions as well as increase fuel economy and power output from a given engine displacement. Most heavy-duty diesel engines are presently equipped with turbochargers, many of which have intercoolers. In the United States, all engines were equipped with these systems by 1991. Recent developments in air charging systems for diesel engines have been primarily concerned with increasing the turbocharger efficiency, operating range, and transient response characteristics. This has been accompanied by improved intercoolers to further reduce the temperature of the intake charge. Tuned intake air manifolds (including some with variable tuning) have also been developed to maximize air intake efficiency in a given speed range.

Turbocharger refinements. Turbochargers for heavy-duty diesel engines are already highly developed, but efforts to improve their performance continue. The major areas of emphasis are improved matching of turbocharger response characteristics to engine requirements, improved transient response, and higher efficiencies. Engine and turbocharger matching is especially critical because of the inherent conflict between the response characteristics of the two types of machines. Engine boost pressure requirements are greatest near the maximum torque speed, and most turbochargers are matched to give near optimal performance at that point. At higher speeds, the exhaust flow rate is greater, and the turbine power output is correspondingly higher. Boost pressure under these circumstances can exceed the engine's design limits, and the excessive turbine backpressure increases fuel consumption. Thus, some compromise between adequate low speed boost and excessive high speed boost must be made.

Variable geometry turbochargers (VGTs). Because of the inherent mismatch between en-

gine response and fixed geometry turbocharger characteristics, a number of engine manufacturers are considering the use of variable geometry turbines. In these systems, the turbine nozzles can be adjusted to vary the turbine pressure drop and power level in order to match the engine's boost pressure requirements. Thus, high boost pressures can be achieved at low engine speeds without wasteful overboosting at high speed. The result is a substantial improvement in low speed torque, transient response, and fuel economy, and a reduction in smoke, NO_x, and PM emissions.

Prototype VGTs have been available for some time, but they have not been used in production vehicles. The major reasons for this are their cost (as much as 50 percent more than a comparable fixed geometry turbocharger), reliability concerns, and the need for a sophisticated electronic control system to manage them. With the forthcoming deployment of electronic engine controls on virtually all U.S. vehicles, these arguments have lost much of their force. VGTs' fuel economy and performance advantages are great enough to outweigh the costs in many applications. As a result, VGTs should be available on a number of production heavy-duty diesel engines in the near future.

Other types of superchargers. A number of alternative forms of supercharging have been studied with respect to overcoming the mismatch between turbocharger and engine response characteristics. The two leading candidates at present are the Sulzer Compresx™ gas dynamic supercharger, and mechanically assisted turbochargers, such as the "three wheel" turbocharger developed by General Motors. The major advantages of these systems are superior low-speed performance and improved transient response. These advantages would be expected to yield some improvement in PM emissions, as well as driveability and torque rise.

Presently, most intercoolers rely on the engine cooling water as a heat sink, since this minimizes the components required. However, this water's relatively high temperature (about 90°C)

limits the benefits available. For this reason, an increasing number of heavy-duty diesel engines are being equipped with low-temperature charge air cooling systems.

The most common type of low-temperature charge air cooler emits heat directly to the atmosphere through an air-to-air heat exchanger mounted on the truck chassis in front of the radiator. Although bulky and expensive, these charge air coolers are able to achieve the lowest charge air temperatures—in many cases, only 10–15°C above ambient. An alternative approach is low temperature air-to-water intercooling, which in the United States has been studied by Cummins Engine. Cummins has chosen to retain the basic water air intercooler, but with drastically reduced radiator flowrates to reduce the water temperature coming from the radiator. This water is then passed through the intercooler before it is used for cooling the rest of the engine.

Intake Manifold Tuning

Tuned intake manifolds have been used for many years to enhance airflow rates on high-performance gasoline engines, and are being considered for some heavy-duty diesel engines. A tuned manifold provides improved airflow and volumetric efficiency at speeds near its resonant frequency, although at the cost of reduced volumetric efficiency at other speeds. At least one medium- and heavy-duty manufacturer is considering a variable resonance manifold in order to improve airflow characteristics at both low and high speeds.

Lubricating Oil Control

A significant fraction of diesel PM (10–50 percent) consists of oil-derived HC and related solid matter. Reduced oil consumption has been a design goal of heavy-duty diesel engine manufacturers for some time, and the current generation of diesel engines already uses fairly less oil than its predecessors. Further reductions in oil consumption are possible through careful attention to cylinder bore roundness and surface finish,

optimization of piston ring tension and shape, attention to valve stem and turbocharger oil seals, and other possible sources of oil loss. However, present technology requires some oil consumption in the cylinder, for its lubricating and corrosion protective functions.

Advances in piston and cylinder tribology could potentially eliminate or greatly reduce oil consumption in the cylinder. Areas such as boundary lubrication and development of low friction ceramic coatings are presently the subjects of much research. The potential for transforming this research into durable and reliable engines on the road is yet to be demonstrated.

AFTERTREATMENT SYSTEMS

In order to achieve very low levels of PM emissions, manufacturers have developed exhaust control devices, cleaning up the exhaust after it leaves the engine. Several devices are available. One is a flow-through oxidation catalytic converter, installed on a vehicle designed to operate on low-sulfur fuel, which can reduce the particulates' soluble organic fraction (SOF) by as much as 90 percent, and may reduce carbon as well. Another is a trap oxidizer control system which can achieve 90 percent or even greater particulate reductions. Catalyst and trap technology can be combined to provide even greater control. Finally, research and development on NO_x aftertreatment systems is taking place, and positive results are beginning to emerge.

Catalytic Converters

A diesel catalytic converter oxidizes a large part of the SOF's HC constituents, as well as gaseous HC, carbon monoxide (CO), odor-creating compounds, and mutagenic emissions. Unlike a catalytic trap, a flow-through catalytic converter does not collect any of the solid PM. This simply passes through in the exhaust. This eliminates the need for a regeneration system with its attendant technical difficulties and costs. The particulate

control efficiency of the catalytic converter is, of course, much less than that of a trap. However, a PM control efficiency of even 25–35 percent is enough to bring many current engines within existing emissions standards.

Diesel catalytic converters have a number of advantages. First, in addition to reducing particulate emissions, the oxidation catalyst greatly reduces HC, CO, and odor emissions. The catalyst is also very efficient in reducing emissions of gaseous and particle-bound toxic air contaminants such as aldehydes, PNA and nitro-PNA. While a precious metal-catalyzed particulate trap would have the same advantages, the catalytic converter is less complex, smaller, and cheaper. In addition, the catalytic converter has little impact on fuel economy or safety, and usually does not require replacement. Also, the catalytic converter is a relatively mature technology—millions of catalytic converters are used in gasoline vehicles, and diesel catalytic converters have been used in underground mining applications for more than 20 years.

Potential sulfate emissions are a major disadvantage of catalytic converters. Precious metal catalysts' tendency to convert SO_2 to particulate sulfates requires the use of low-sulfur fuel. Otherwise, sulfate emissions increases would more than counterbalance the decrease in SOF. Fortunately, Europe, Japan, and the United States have already decided to reduce diesel fuel sulfur content, making catalyst technology viable.

An oxidation catalyst causes chemical reactions without being changed or consumed. An oxidation catalytic converter consists of a stainless steel canister that typically contains a honeycomb-like structure called a substrate. There are no moving parts, just interior surfaces on the substrate coated with catalytic metals such as platinum or palladium. It is called an oxidizing catalyst because it transforms the pollutant, in this case SOF, into harmless gases by means of oxidation. The oxidation catalyst has been optimized so that engine durability and reliability are unaffected, and no fuel penalties will occur.

Oxidation catalysts are able to control a significant portion of particulate SOF. For example,

one study reported that oxidation catalysts could reduce particulate SOF by 90 percent under certain operating conditions, and could reduce total particulate emissions by 40–50 percent. SOF destruction is important since these emissions contain numerous chemical pollutants of particular concern to health experts. Another benefit of the oxidation catalyst is that it also controls gaseous hydrocarbon and CO emissions in exhaust by 80–90 percent. Finally, catalysts noticeably reduce diesel exhaust odor.

Trap Oxidizers or Filters

A trap oxidizer system consists of a durable particulate filter (the “trap”) positioned in the engine exhaust stream, along with some means for cleaning the filter by burning off (“oxidizing”) the collected PM. Building a filter capable of collecting diesel soot and other PM from the exhaust stream is a straightforward task, and a number of effective trapping media have been developed and demonstrated. The most challenging problem of trap oxidizer system development was the process of “regenerating” the filter by burning off the accumulated PM.

Diesel PM consists primarily of a mixture of solid carbon coated with heavy HCs. The ignition temperature of this mixture is about 500–600°C, which is above the normal range of diesel engine exhaust temperatures. Thus, special means are needed to assure regeneration. Furthermore, once ignited, this material burns at very high temperatures which can easily melt or crack the particulate filter. Initiating and controlling the regeneration process to ensure reliable regeneration without damaging the trap is the central engineering problem of trap oxidizer development.

Numerous techniques for regenerating particulate trap oxidizers have been proposed. These approaches can generally be divided into two groups—passive and active systems. Passive systems must attain conditions required for regeneration during normal vehicle operation. The most promising approaches require a catalyst (either as a coating on the trap or as a fuel additive)

in order to reduce the collected PM ignition temperature. Regeneration temperatures as low as 420°C have been reported with catalytic coatings, and even lower temperatures are achievable with fuel additives.

Active systems monitor PM buildup on the trap, and trigger specific regeneration actions when needed. A wide variety of regeneration triggers have been proposed such as diesel fuel burners, electric heaters, and catalyst injection systems.

Passive regeneration systems face special problems from heavy-duty vehicles. Exhaust temperatures from heavy-duty diesel engines are normally low, and recent developments such as charge air cooling and increased turbo charger efficiency reduce them further. Under some conditions, it would be possible for a truck to drive for many hours without exceeding the exhaust temperature (400–450°C) required to trigger regeneration.

Engine and catalyst manufacturers have experimented with a wide variety of catalytic materials and treatments to assist in trap regeneration. Good results have been obtained both with precious metal (platinum, palladium, rhodium, silver) and base metal (vanadium, copper) catalysts. Precious metal catalysts are effective in oxidizing gaseous HC and CO and particulate SOF, but are relatively ineffective at promoting soot oxidation. Unfortunately, these metals also promote the oxidation of SO₂ to particulate sulfates such as sulfuric acid (H₂SO₄). In contrast, the base metal catalysts are effective in promoting soot oxidation, but have little effect on HC, CO, NO_x or SO₂. Many experts believe, that ultimately, precious metal catalysts must be an important element of an effective particulate control system because it specifically attacks the “bad actors.”

Catalyst coatings also have a number of advantages in active systems. The reduced ignition temperature and increased combustion rate (due to the catalyst) mean that the regeneration system needs less energy. Regeneration will also occur spontaneously under most duty cycles, greatly reducing the number of times the regeneration system must operate. The spontaneous

regeneration capability also provides some insurance against regeneration system failure. Finally, the use of a catalyst may make a simpler regeneration system possible.

Although normal heavy-duty diesel exhaust temperatures are not high enough under all operating conditions to provide reliable regeneration for a catalyst-coated trap, exhaust temperature can easily be increased by changing engine operating parameters. Retarding the injection timing, bypassing the intercooler, throttling the intake air (or cutting back on a variable geometry turbocharger), or increasing the EGR rate will increase the exhaust temperature dramatically. Applying these measures consistently would seriously degrade fuel economy, engine durability, and performance. However, an electronic control system can selectively apply these measures to regenerate the trap. In addition, since they are normally needed only at light loads, effects on durability and performance should be imperceptible.

Fuel additives may play a key role in trap-based systems, although concerns have been raised about metallic additives' possible toxicity. Cerium-based additives have not yet raised these concerns, and recent studies of buses in Athens, Greece, have shown encouraging results. These additives were able to lower engine-out particulate emissions as well as facilitate regeneration. Ongoing studies in South Korea continue to show high promise also. Further analysis of health effects assessment may be required for cerium-based additives.

In order to protect the filter from overheating and possible damage, some trap systems have an exhaust gases bypass which is triggered only when exhaust temperatures reach critical levels. The bypass operates infrequently and only for a very short time. Systems also have been designed with dual filters—one filter collects while the other is being regenerated.

Traps are being further developed for optimizing regeneration systems which are simple, reliable and reasonably priced to demonstrate durability of the trap system in real world operation.

Nitrogen Oxide Reduction Techniques

Under certain conditions NO_x can be chemically reduced to form gaseous oxygen and nitrogen. This process is used in modern closed-loop three-way catalyst-equipped gasoline vehicles to control NO_x emissions. However, catalytic NO_x reduction as used in gasoline vehicles is inapplicable to diesels. Because of their heterogeneous combustion process, diesel engines require substantial excess air, and their exhaust inherently contains significant excess oxygen. The three-way catalysts used on automobiles require a precise stoichiometric mixture in the exhaust in order to function. In the presence of excess oxygen, their NO_x conversion efficiency rapidly approaches zero.

A number of aftertreatment NO_x reduction techniques which work in an oxidizing exhaust stream are currently available or under development for stationary pollution sources. These include selective catalytic reduction (SCR); selective non-catalytic reduction (Thermal Denox™); and reaction with cyanuric acid (RapReNox™). However, each of these systems requires a continuous supply of some reducing agent, such as ammonia or cyanuric acid, to react with the NO_x . Because this agent needs to be frequently replenished, and it is difficult to ensure that the replenishment is performed when needed, such systems are considered impractical for vehicular use.

A report prepared by Acurex (under contract to the California Air Resources Board), "Technical Feasibility of Reducing NO_x and Particulate Emissions From Heavy-Duty Engines," concluded that NO_x can potentially be reduced as low as 2.5 grams per BHP-hr. This standard would require a combination of some or all of the following emissions control approaches: very high pressure fuel injection, variable geometry turbocharging, air-to-air aftercooling, optimized combustion, electronic unit injections with minimized sac volumes, rate shaping, exhaust gas recirculation, and sophisticated electronic control of all engine systems. Such controls would substantially increase cost and fuel consumption.

Most of the devices described in the Acurex report are in relatively early stages of development and would require extensive changes in heavy-duty diesel-powered engines compared to today's designs.

Status of Aftertreatment Applications

In Europe, over 500,000 diesel automobiles each year are equipped with catalysts, and virtually all new diesel cars sold in Austria, France, and Germany come so equipped. Public demand for clean diesels and tax incentives are spurring the use of these devices. "Oxidation catalysts can lower CO, HC and particulate emissions considerably, and also improve the odor of diesel exhaust."¹ After Step 2 light duty vehicle standards are introduced, virtually all new diesel light-duty vehicles sold in Europe are expected to be equipped with at least an oxidation catalyst by 1997.

In 1994, a number of U.S. engine manufacturers offered catalyst-equipped trucks capable of meeting the 0.1 PM standard. Indeed, catalysts are being used on a significant number of 1994 model year heavy-duty (8,500–33,000 pounds GVWR range) trucks to help manufacturers meet tougher PM standards. Also, engine manufacturers will use catalysts to meet the 0.07 bus standard, and may be able to meet the 0.05 standard on some bus engines. Recently, 200 school buses with Caterpillar 3116 engines were equipped with catalysts as part of a demonstration program sponsored by the California. Catalysts will also be an available option for urban bus engines rebuilt under USEPA's bus rebuild requirements.

NO_x reduction catalysts (De NO_x catalysts), currently at the prototype stage, offer the potential for considerably lower NO_x emissions, and may begin to be applied to some vehicle models over the next few years."²

By the year 2000, further improvements will have to be made to all passenger car diesel engines in order to attain proposed standards—0.04 grams per kilometer of PM and 0.5 grams per kilometer each of HC and NO_x . "To achieve [these levels,] both engine types, the ID and the

DI, must be equipped with sophisticated emissions control systems which include:

- Electronically controlled injection system;
- Injection rate shaping (at least for the DI);
- Multi valve technology;
- Turbocharging;
- Intercooling;
- Controlled EGR; and
- Oxidation Catalyst³

“Hydrocarbon levels of less than 0.03 grams per kilometer over the European emissions cycle are possible with a well optimized catalyst equipped diesel car, which is comparable with the requirements of the California Low Emissions Vehicle (LEV) standards.”⁴

For heavy-duty vehicles, “[T]o comply with the European Stage III standards all engines are likely to feature 4 valve per cylinder combustion systems, and very high pressure injection systems with injection pressure in excess of 1500 bar. These engines will also incorporate new technologies for NO_x reduction, such as the use of pilot injection or exhaust gas recirculation (EGR). If EGR is employed, significant problems associated with engine durability will need to be overcome. However, these engines will offer the pos-

sibility of achieving zero visible smoke under all operating conditions.

“To achieve standards projected beyond the year 2000 there is already significant research and development on NO_x reduction (DeNO_x) catalysts. Development of particulate traps and regeneration technology is also underway, and if successful, this will enable further significant reductions in exhaust particulate emissions.”⁵

Engine manufacturers throughout the world are subjecting trap systems to a full range of evaluation. In addition, devices continue to be evaluated by other parties interested in diesel particulate control.

Trap oxidizers are not only being developed for new vehicles, but also as a control device that can be retrofitted to existing trucks and buses. In fact, traps already have been retrofitted on urban buses and fire trucks in a number of cities around the world.

EFFECT ON FUEL CONSUMPTION AND COSTS

Diesel vehicle fuel economy is likely to see an overall operating costs increase of about 2 per-

Table C.1: Cost of Diesel Engine Exhaust Emissions Control Technology

Technology	Estimated extra cost as percent of engine first cost (excluding development costs)
Baseline engine, no emissions control equipment. Developed for performance only.	Nil
Injection timing retard	Nil
Low sac volume/valvecovering orifice nozzle	Minimal
Turbocharging	3-5 percent
Charge cooling	5-7 percent
Improved high pressure fuel injection	13-15 percent
High pressure fuel injection with electronic control	14-16 percent
Variable geometry turbocharging (assuming already applied to engine)	1-3 percent
Particulate trap	4-25 percent

Source: ECMT 1990

cent as a result of stringent exhaust emissions limits. The techniques available for reducing NO_x emissions (primarily ignition retard and EGR) will lead to poor fuel economy; other engine improvements such as increased use of turbocharging and charge cooling, better control of injection rates, and timing may offset some of the fuel efficiency losses.

Additional equipment (e.g., charge coolers or particulate traps) needed to comply with exhaust emissions requirements are likely to increase vehicle costs. More advanced equipment, such as electronic fuel injection systems or variable geometry turbochargers will increase costs initially, but those costs should come down when such equipment becomes standard. Vehicle maintenance costs are not likely to increase except for

particulate traps, which have not yet been proven durable. Table C.1 shows estimated cost increases for individual engine modifications that will be needed to meet future emissions standards.

ENDNOTES

1. Ricardo. 1994. "Automotive Diesel Engines & the future."
2. Ricardo. 1994. Op. cit.
3. Pisching, F. 1994. "Vehicle Engine Development Trends under Future Boundary Conditions," SAE # 945001, Fisita 94.
4. Ricardo. 1994. "Automotive Diesel Engines & the future."
5. Ricardo. 1994. Op. cit.

APPENDIX D: INTERNATIONAL EMISSION AND FUELS STANDARDS

Table D.1: Canada and US Tier 1 Emission Standards (1994-)—Light-Duty Vehicles and Trucks

Table D.2: U.S. Tier 1 Emission Standards (1994-)—Heavy-Duty Engines and Urban Buses

Table D.3: E.U. Light-Duty Vehicle Emission Standards (1996-)

Table D.4: E.U. Heavy-Duty Diesel Vehicle Emission Standards (1993–2000)

Table D.5: Japan Vehicle Emission Standards (1997)

Table D.6: Hong Kong Vehicle Emission Standards (1997)

Table D.7: South Korea Vehicle Emission Standards (1996)

Table D.8: Current Exhaust Emissions Standards Republic of Singapore

Table D.9: Diesel Driven Exhaust Emission Standards Republic of Singapore (effective July 1997)

Table D.10: Emission Standards for Japan

Table D.11: Hong Kong New Vehicle Emission Standards (as of 1 April 1995)

Table D.12: Hong Kong Automotive Fuel Specifications

Table D.13: Malaysia Gasoline Vehicle Emissions Standards

Table D.14: Malaysia Diesel Vehicle Emissions Standards

Table D.15: International Vehicle Exhaust Emission Regulations—Automobiles

Table D.16: International Vehicle Exhaust Emission Regulations—Light Duty Trucks

Table D.17: International Vehicle Exhaust Emission Regulations—Heavy Duty Trucks

Table D.18: Lead Added to Gasoline (1990–2000)

Table D.1: Canada and US Tier 1 Emission Standards (1994-)—Light Duty Vehicles and Trucks

Vehicle	GVWR (lbs)	Fuel	LVW or ALVW (lbs)	Mileage (miles)	NMHC (g/mi)	CO (g/mi)	NOx (g/mi)	PM (g/mi)
Light-Duty Vehicles	all	non-diesel	all	50,000	0.25	3.4	0.4	0.08
	all	diesel	all	5,000	0.25	3.4	1.0	0.08
	all	non-diesel	all	100,000	0.31	4.2	0.60	0.10
	all	diesel	all	100,000	0.31	4.2	1.25	0.10
Light-Duty Trucks	0 - 6,000	non-diesel	0 - 3,750	50,000	0.25	3.4	0.4	0.08
	0 - 6,000	diesel	0 - 3,750	50,000	0.25	3.4	1.0	0.08
	0 - 6,000	non-diesel	3,751 - 5,750	50,000	0.32	3.4	0.7	0.08
	0 - 6,000	diesel	3,751 - 5,750	50,000	0.32	3.4	0.7	0.08
	0 - 6,000	non-diesel	0 - 3,750	100,000	0.31	4.2	0.60	0.10
	0 - 6,000	diesel	0 - 3,750	100,000	0.31	4.2	1.25	0.10
	0 - 6,000	non-diesel	3,751 - 5,750	100,000	0.40	5.5	0.97	0.10
	0 - 6,000	diesel	3,751 - 5,750	100,000	0.40	5.5	0.97	0.10
Heavy Light-Duty Trucks	>6,000	non-diesel	3,751 - 5,750	50,000	0.32	4.4	0.7	—
	>6,000	diesel	3,751 - 5,750	50,000				
	>6,000	non-diesel	>5,750	50,000				
	>6,000	diesel	>5,750	50,000				
	>6,000	non-diesel	3,751 - 5,750	120,000	0.46	6.4	0.98	0.10
	>6,000	diesel	3,751 - 5,750	120,000	0.46	6.4	0.98	0.10
	>6,000	non-diesel	>5,750	120,000	0.56	7.3	1.53	0.12
	>6,000	diesel	>5,750	120,000	0.56	7.3	1.53	0.12

Note: GVWR = gross vehicle weight registered; LVW = loaded vehicle weight; ALVW = axle loaded vehicle weight

Table D.2: U.S. Tier 1 Emission Standards (1994-)—Heavy duty Engines and Urban Buses

Vehicle	Fuel	GVWR (lbs)	Mileage	NMHC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
Heavy Duty Trucks	non-diesel	< 14,000	110,000	1.1	14.4	4.0	--
	non-diesel	>14,000		1.9	37.1	4.0	--
	diesel	urban buses	110,000	1.3	15.5	4.0	0.05
	diesel	trucks		1.3	15.5	4.0	0.10

Table D.3: E.U. Light Duty Vehicle Emission Standards (1996-)

Vehicle	GVWR(kg)	Fuel	HC+NOx(g/km)	CO(g/km)	PM(g/km)
Light Duty Vehicles	all	non-diesel	05	20	-
	all	diesel	07	10	008
	all	direct injection diesel	10	09	010
Light Duty Trucks	0-1250	all	097	272	014
	1251-1700	all	140	517	019
	>1700	all	170	690	025

Table D.4: E.U. Heavy Duty Diesel Vehicle Emission Standards (1993-2000)

Category	Engine Power	HC (g/kw-hr)	CO (g/kw-hr)	NOx (g/kw-hr)	PM (g/kw-hr)
Euro1 1993	< 85 Kw	1.1	4.5	8.0	0.63
	> 85 Kw	1.1	4.5	8.0	0.36
Euro 2 1996	all	1.1	4.0	7.0	0.15
Euro 3 2000		TBD		TBD	TBD

Table D.5: Japan Vehicle Emission Standards (1997)

Vehicle	GVWR (tons)	Fuel	HC (g/km)	CO (g/km)	NOx (g/km)	PM (g/km)
Light-Duty Vehicles	< 1.7	non-diesel				
		diesel			0.4	0.08
Light-Duty Trucks	1.7<GVW<2.5	non-diesel				
		diesel	0.62	2.70	0.70	0.09
HDE (g/kWh)	2.5<GVW<3.5	non-diesel				
		diesel			4.5	0.25
	3.5 < GVW < 12	non-diesel				
		diesel			4.5	0.25
	> 12	non-diesel				
		diesel			4.5	0.25

Table D.6: Hong Kong Vehicle Emission Standards (1997)

Vehicle	GVWR (tons)	Fuel	HC (g/km)	CO (g/km)	NOx (g/km)	PM (g/km)
Light-Duty Vehicles	< 1.7	non-diesel				
		diesel			0.63	0.12
Light-Duty Trucks	1.7<GVW<2.5	non-diesel				
		diesel				
HDE (g/kWh)	2.5<GVW<3.5	non-diesel				
		diesel				
	3.5<GVW<12	non-diesel				
		diesel				
	>12	non-diesel				
		diesel				

Table D.7: South Korea Vehicle Emission Standards (1996)

Vehicle	GVWR (tons)	Fuel	HC (g/km)	CO (g/km)	NOx (g/km)	PM (g/km)
Light-Duty Vehicles	all	non-diesel				
		diesel	0.25	2.11	0.62	0.08
Light-Duty Trucks	< 2	non-diesel				
		diesel	0.5	6.21	1.43	0.31
HDE (g/kWh)	all	non-diesel				
		diesel	1.2	4.9	11.0	0.9

Table D.8: Current Exhaust Emissions Standards Republic of Singapore

Type of Vehicle	Emission Standard (for Registration)	Implementation Date
Petrol-driven vehicles	European Union Directive 91/441/EEC (Consolidated Emissions Directive) or the JIS 78 Emission Standard	1 July 94
Diesel-driven vehicles	UN/ECE R 24.03 Black Smoke Emission Standard	1 January 91
Motorcycles & Scooters	United States Code of Federal Regulations (US 40 CFR 86.410-80 Emission Standard)	1 October 91

Table D.9: Diesel Driven Exhaust Emissions Standards Republic of Singapore (effective July 1997)

Vehicle Type	Emission Standard Applicable	Implementation Date
Passenger Cars	93/59/EEC	1 July 97
	JIS 94 Standard	1 July 97 - 30 June 98
Light Commercial Vehicles	93/59/EEC	1 July 97
	JIS 93 Standard	1 July 97 - 30 June 98
Heavy Duty Vehicles	91/542/EEC Stage 1	1 July 97
	JIS 94 Standard	1 July 97 - 30 June 98

Table D.10: Emission Standards for Japan

Motor Vehicle Category	Permissible limits recommended for Target Values (mean-Value)					Measurement Mode
	CO	HC	NOx	PM	Smoke	
Small and mini-sized two-wheeled motor vehicles; With Four-cycle engines	13.0 g/km	200 g/km	0.30 g/km	-	-	ISO 6460 (attached Measurement mode)
1st and 2nd class motor-driven cycles with Two-cycle engines	8.0 g/km	300 g/km	0.10 g/km	-	-	ISO 6460 (attached Measurement mode)
Gasoline-and LPG-fueled mini-sized trucks (excluding those with two-cycle engines)	6.50 g/km	0.25 g/km	0.25 g/km	-	-	10 • 15 Mode
Gasoline and LPG-fueled, medium and heavy-duty motor vehicles (excluding passenger vehicles with seating capacity of less than 11)	1.7t < GVW < 2.5t 6.50 g/km	0.25 g/km	-	-	-	10 • 15 Mode
Diesel-powered heavy-duty vehicles, with 12t < GVW	51.0 g/kwh	180g/kwh	-	-	-	Gasoline 13 Mode
	-	-	4.50 g/kwh	0.25 g/kwh	25%	Diesel 13 Mode

Table D.11: Hong Kong New Vehicle Emission Standards (as of 1 April 1995) (pt. 1)

Class of Vehicle	Positive Ignition Engine		Compression Ignition Engine		
	Test Procedure	Limits	Test Procedure	Limits	
All			72/306/EEC Free Acceleration Smoke as amended by 89/491/EEC (light absorption coefficient K, m-1)	K-1.20	
Private Car / Taxi	US FTP 75 (g/km)	HC - 0.26	US FTP 75 (g/km)	HC - 0.26	
		CO - 2.10		CO - 2.10	
		NOx-0.63		NOx-0.63	
	Japan 10.15 mode (g/km)	HC - 0.39	Japan 10.15 mode (g/km)	HC - 0.62	
		CO - 2.70		CO - 2.70	
		NOx-0.48		NOx-0.72	
	93/59/EEC Type 1 (g/km)	HC+NOx-0.97 CO-2.72	VW < = 1.265 tonne	NOx-0.84	
			VW > 1.265 tonne	PM-0.34	
			93/59/EEC Type 1 (g/km)	HC+NOx-0.97 CO-2.72 PM-0.14	
	maximum mass exceeds 2,500 tonne OR designed to carry more than 6 occupants including driver				
	RW <=1.250 tonne	HC+NOx-0.97 CO - 2.72	RW < = 1.250 tonne	HC+NOx-0.97	
				CO- 2.72 PM- 0.14	
1.250 tonne < RW < + 1.700 tonne	HC+NOx-1.4 CO-5.17	1.250 tonne < RW < =1.700 tonne	HC+NOx-1.4		
			CO- 5.17 PM-0.19		
RW > 1.700 tonne	HC+NOx - 1.7 CO - 6.9	RW > 1.700 tonne	HC+NOx 1.7		
			CO - 6.9 PM-0.25		

Table D.11: Hong Kong New Vehicle Emission Standards (as of 1 April 1995) (pt. 2)

Class of Vehicle	Positive Ignition Engine		Compression Ignition Engine			
	Test Procedure	Limits	Test Procedure	Limits		
Light Goods Vehicle / Light Bus / with DW not more than 1.7 tonne	US FTP 75 (g/km)	HC - 0.50	US FTP 75 (g/km)	HC - 0.50		
		CO - 6.20		CO - 6.20		
		NOx-0.75		NOx-0.75		
	Japan 10.15 mode (g/km)	HC - 0.39	Japan 10.15 mode (g/km)	HC - 0.62		
		CO - 2.70		CO - 2.70		
		NOx-0.48		NOx-0.84		
	93/59/EEC Type 1 (g/km) RW < + 1.250 tonne	93/59/EEC Type 1 (g/km) RW < = 1.250 tonne	HC+NOx-0.97	93/59/EEC Type 1 (g/km) RW < = 1.250 tonne	HC+NOx-0.97	
			CO - 2.72		CO - 2.72	
			PM - 0.14		PM - 0.14	
		1.250 tonne < RW < = 1.700 tonne	93/59/EEC Type 1 (g/km) 1.250 tonne < RW < = 1.700 tonne	HC+NOx- 1.4	93/59/EEC Type 1 (g/km) 1.250 tonne < RW < = 1.700 tonne	HC+NOx- 1.4
				CO - 5.17		CO - 5.17
				PM - 0.19		PM - 0.19
Light Goods Vehicle / Light Bus / with DW more than 1.7 tonne but not more than 2.5 tonne	US FTP 75 (g/km)	HC - 0.50	US FTP 75 (g/km)	HC - 0.50		
		CO - 6.20		CO - 6.20		
		NOx-1.10		NOx-1.10		
	Japan 10.15 mode (g/km)	Japan 10.15 mode (g/km)	HC - 2.70	Japan 10.15 mode (g/km)	HC - 0.62	
			CO - 17.0		CO - 2.70	
			NOx-0.98		NOx-1.82	
	93/59/EEC Type 1 (g/km) RW < = 1.250 tonne	93/59/EEC Type 1 (g/km) RW < = 1.250 tonne	HC+NOx- 0.97	93/59/EEC Type 1 (g/km) RW < = 1.250 tonne	HC+NOx-0.97	
			CO - 2.72		CO- 2.72	
			PM-0.14		PM-0.14	
		1.250 tonne < RW < = 1.700 tonne	93/59/EEC Type 1 (g/km) 1.250 tonne < RW < = 1.700 tonne	HC+NOx- 1.4	93/59/EEC Type 1 (g/km) 1.250 tonne < RW < = 1.700 tonne	HC+NOx-1.4
				CO - 5.17		CO - 5.17
				PM - 0.19		PM - 0.19
RW > 1.700 tonne	93/59/EEC Type 1 (g/km) RW > 1.700 tonne	HC+NOx - 1.7	93/59/EEC Type 1 (g/km) RW > 1.700 tonne	HC+NOx -1.7		
		CO - 6.9		CO - 6.9		
		PM - 0.19		PM - 0.19		

Table D.11: Hong Kong New Vehicle Emission Standards (as of 1 April 1995) (pt. 3)

Class of Vehicle	Positive Ignition Engine		Compression Ignition Engine		
	Test Procedure	Limits	Test Procedure	Limits	
Light Goods Vehicle / Light Bus / with DW more than 2.5 tonne but not more than 3.5 tonne	US FTP 75 (g/km)	HC - 0.50	US FTP 75 (g/km)	HC - 0.50	
		CO - 6.20		CO - 6.20	
		NOx-1.10		NOx-1.10	
	Japan HDP 13 mode (g/kwh)	HC - 7.90	93/59/EEC Type 1 (g/km)	PM - 0.28	
		CO - 136		RW <= 1.250 tonne	HC+NOx-0.97
		NOx-7.20		CO - 2.72	
	93/59/EEC Type 1 (g/km)	RW <= 1.250 tonne	HC+NOx - 0.97	PM - 0.14	
				CO - 2.72	CO - 5.17
				PM - 0.19	PM - 0.19
	1.250 tonne < RW <= 1.700 tonne	HC+NOx-1.4	1.250 tonne < RW <= 1.700 tonne	HC+NOx-1.4	
CO - 5.17				CO - 5.17	
PM - 0.19				PM - 0.19	
RW > 1.700 tonne	HC+NOx- 1.7	RW > 1.700 tonne	HC+NOx-1.7		
			CO - 6.9	CO - 6.9	
			PM - 0.25	PM - 0.25	
Goods Vehicle / Light Bus / Bus / with DW more than 3.5 tonne	US HDO Transient (g/kwh)	HC - 2.55	US HDD Transient (g/Kwh)	HC - 1.74	
		CO - 49.7		CO - 20.8	
		NOx -6.70		NOx-8.04	
	Japan HDP 13 mode (g/kwh)	HC - 7.90	91/542/EEC (g/kwh)	PM - 0.80	
		CO - 136		HC - 1.1	
		NOx-7.20		CO - 4.5	
			Engine Power <= 85 kw	PM - 0.61	
			Engine Power > 85 kw	PM - 0.36	

FTP - Federal Test Procedure DW - Design Weight RW - Reference Mass

HDP -Heavy Duty Petrol (Gasoline) HDO-Heavy Duty Otto HDD-Heavy Duty Diesel

Table D.12: Hong Kong Automotive Fuel Specifications

Diesel Properties	1 April 1995	1 April 1997	TestMethod
Sulphur (% by Wt.)	.20 Maximum	0.05 Maximum	ASTM D4294
Cetane Number	50 Minimum	50 Minimum	ASTM D613
Viscosity (mm ² /s)	2.0-4.5	2.0-4.5	ASTM D445
Distillation (C)			ASTM D86
IBP	Report	Report	
10 % Volume	Report	Report	
50 % Volume	Report	Report	
90 % Volume	357 Maximum	Report	
95% Volume		370 Maximum	
Density (kg/l)	.820-.860	.820-.860	ASTM D1298
Unleaded Petrol Properties	1 April 1995	1 April 1997	Test Method
Lead (g/L)	.013 Maximum	.005 Maximum	ASTM D3237
Sulphur (% Mass)	.10 Maximum	.050 Maximum	ASTM D1266
Motor Octane Number	85.0 Minimum	85.0 Minimum	ASTM D2700
Research Octane Number	95.0 Minimum	95.0 Minimum	ASTM D2699
Benzene (% Vol)	5 % Max.(voluntary)	5 % Maximum	ASTM D4420
Methanol (% Vol) (a)		3 % Maximun	ASTM D5599
Ethanol (% Vol) (a)		5 % Maximum	ASTM D5599
Iso-propyl alcohol (% Vol) (a)		5 % Maximum	ASTM D5599
Tertiary butyl alcohol (% Vol) (a)		7 % Maximum	ASTM D5599
Iso-butyl alcohol (% Vol) (a)		7 % Maximum	ASTM D5599
Ethers containing 5 or more carbon atoms per molecule (% Vol) (a)		10 % Maximun	ASTM D5599
Other organic oxygenates (% Vol) (a)		7 % Maximum	ASTM D5599
Mixture of all organic oxygenates			

Table D.13: Malaysia Gasoline Vehicle Emissions Standards

Emissions Standard	Effective Date
ECE R 24.03 (for all diesel vehicles)	September 1, 1996
ECE R 49 (for heavy-duty vehicles having GVW > 3.5 tons)	September 1, 1997
ECE R 15.04 (for vehicles having GVW <3.5 tons)	September 1, 1997
93/59/EEC (for vehicles having GVW up to 3.5 tons)	January 1, 1997 (new models)
ECE R 49-02 (Euro 1) (for having duty vehicles having GVW up to 3.5 tons)	January 1, 1997 (new models)

Table D.14: Malaysia Diesel Vehicle Emissions Standards

Emissions Standard	Effective Date
ECE R 15-04 (for vehicles having GVW <3.5 tons)	November 1, 1996
91/441/EEC (for vehicles having GVW >2.5 tons)	January 1, 1997 (new models)
93/59/EEC (for vehicles having GVW <3.5 tons)	January 1, 1997 (new models)
94/12/EC (for vehicles having GVW up to 2.5 tons)	January 1, 1997 (new models)

GVW = gross vehicle weight

Table D.15: International Vehicle Exhaust Emission Regulations—Automobiles

Country	New Automobiles					Used Automobiles				
	Yr. of Reg.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)	Yr. of Reg.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)
Anguilla	No Regulations									
Argentina	1995	N/A	Jan.96-400	'96-1.4	Jan.95-2.5	1995	N/A	'83-91-900	N/D	'83-91-4.5
			Jan.97-250	'97-0.6	Jan.97-05			'92-92-600		'92-92-3.0
			Jan.99-250	'99-0.6	Jan.99-0.5			'95-400		'95-2.5
Barbados	No Regulations									
Bermuda	No Regulations									
Bolivia	1995	N/A	200	1.13-1.90	2.0	1995	N/A	400-700	1.13-1.90	3.0-6.0
Brazil	1992	N/A	'92-1.2 g/km	'92-1.4	'92-12 g/km	N/A	N/A	N/A	N/A	N/A
			'97-0.3 g/km	'97-0.6	'97-2.0 g/km					
Chile	1991	N/A	0.25 g/km	0.62	2.11 g/km	1994	N/A	500-800	-	3.5-4.5
Columbia	1996	N/A	0.25 g/km	0.62	2.10 g/km	1996	N/A	750	-	4.5
Costa Rica	1996	N/A	350	800 ppm	2.0	1995	N/A	No limits	No limits	4.5
Dominican Republic	No regulations									
El Salvador	There is a law controlling emissions, but there are no regulations									
Haiti	No regulations									
Honduras	1999	N/A	126	-	0.5	1,998	N/A	601	-	5.5
Jamaica	No Regulations									
Netherlands Antilles	No Regulations									
Nicaragua	1997	0.013	125	-	0.5	1997	0.013	800	-	4.5
Paraguay	No Regulations									
Peru	No Regulations, except for CO limits for one historical area in Lima									
Trinidad & Tobago	No Regulations									
Uruguay	No Regulations									

N/A=Not Applicable N/D=No Data

Table D.16: International Vehicle Exhaust Emission Regulations—Light Duty Trucks

Country	New Light Duty Trucks					Used Light Duty Trucks				
	Yr. of Reg.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)	Yr. of Reg.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)
Anguilla	No Regulations									
Argentina	1995	N/A	Jan.95-400	'95-2.5	Jan.95-2.5	1995		'83-91-900	N/D	'83-91-4.5
			Jan.97-250	'97-06	Jan.97-0.5			'92-92-600	'92-92-3.0	
			Jan.99-260	'99-0.6	Jan.99-0.5			N/A	'95-400	'95-2.5
Barbados	No Regulations									
Bermuda	No Regulations									
Bolivia	1995	N/A	200	1.13-2.57	2.0	1995	N/A	400-700	1.13-2.57	3.0-6.0
Brazil	1994	'96-0.4 g/kwh	'94-2.45g/kwh	'94-14.4g/kwh	'94-11.2g/kwh	N/A	N/A	N/A	N/A	N/A
		'00-0.15g/kwh	'96-1.23g/kwh	'96-9.0g/kwh	'96-4.9g/kwh					
			'00-1.10g/kwh	'00-7.0g/kwh	'00-4.0g/kwh					
Chile	1991	N/A	0.5g/km	1.43g/km	6.2g/km	1994	N/A	500-800	-	3.5-4.5
Columbia	1996	N/A	1.05g/km	1.43g/km	11.5g/km	1996	N/A	750	-	4.5
Costa Rica	1995	N/A	350	800g/km	2.0	1995	N/A	No Limits	No Limits	4.5
Dominican Republic	No Regulations									
El Salvador	There is a law controlling emissions, but there are no regulations									
Haiti	No Regulations									
Honduras	-	N/A	-	-	-	-	N/A	-	-	-
Jamaica	No Regulations									
Nicaragua	-	N/A	-	-	-	-	N/A	-	-	-
Paraguay	No Regulations									
Peru	No Regulations, except for CO limits for one historical area in Lima									
Trinidad & Tobago	No Regulations									
Uruguay	No Regulations									

N/A=Not Applicable N/D=No Data

Table D.17: International Vehicle Exhaust Emission Regulations—Heavy Duty Trucks

Country	New Heavy Duty Trucks					Used Heavy Duty Trucks				
	Yr. of Reg.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)	Yr. of REG.	Lead (g/L)	HC (ppm)	NO2 (g/km)	CO (%)
Anguilla	No Regulations									
Argentina	1995		Jan.95-600	Jan.95-14.4	Jan.95-3.0	1995		Jan.95-600	N/D	Jan.97-3.0
			Jan.97-400	Jan.97-2.5	Jan.97-2.5			Jan.97-400		Jan.95-2.5
Barbados	No Regulations									
Bermuda	No Regulations									
Bolivia	1996	-	200	4.50	2.0	1995	-	400-700	4.5	3.0-6.0
Brazil	1994	'96-0.4g/kwh	'94-2.45g/kwh	'94-14.4g/kwh	'94-11.2g/kwh	N/A	N/A	N/A	N/A	N/A
		'00-0.15g/kwh	'96-1.23g/kwh	'96-9.0g/kwh	'96-4.9g/kwh					
			'00-1.10g/kwh	'00-7.0g/kwh	'00-4.0g/kwh					
Chile	-									
Columbia	1996	N/A	10.0g/km	10.0g/km	25.0g/km	1996	N/A	750	-	4.5
Costa Rica	1995	N/A	350	800ppm	2.0	1995	N/A	No limits	No limits	4.5
Dominican Republic	No Regulations									
El Salvador	There is a law controlling emissions but there are no regulations									
Haiti	No Regulations									
Honduras	-	N/A	-	-	-	-	N/A	-	-	-
Jamaica	No Regulations									
Nicaragua	-	N/A	-	-	-	-	N/A	-	-	-
Paraguay	No Regulations									
Peru	No Regulations, except for CO limits for one historical area in Lima									
Trinidad & Tobago	No Regulations									
Uruguay	No Regulations									

N/A=Not Applicable N/D=No Data

Table D.18: Lead Added to Gasoline (1990-2000)

Country	Actual Additions (Tons of Pb/Year)			Planned Additions (Tons of Pb/Year)			Last Year Leaded Gasoline Available
	1990	1993	1995	1996	1998	2000	
Argentina Eg3	45	60	0	0	0	0	1996
Esso	1490	960	34	0	0	0	1996
Refisan	Est.100	Est.100	0	0	0	0	1996
YPF(1 Ref.)	400	290	0	0	0	0	1996
Barbados	Est.125	116	107	127	Est.75	EST.25	2000
Bolivia	19.8	23.3	0	0	0	0	1995
Brazil	0	0	0	0	0	0	1992
Chile(1 Ref.)	310	290	250	Est.250	Est.200	Est.200	N/R
Columbia	Est.0	0	0	0	0	0	1990
Costa Rica	71	86	57	12.6	0	0	1996
Dominican Republic	438	Est. 431	452	400	Est.375	Est.350	no date
Ecuador	2400	1466	1328	569	0	0	2000
El Salvador	138	225	202	84	0	0	1996
Guatemala	Est.140	0	0	0	0	0	1991
Honduras	Est.125	0	0	0	0	0	Ref. S/D in 1992
Jamaica	2700	1022	1217	973	486	243	no date
Mexico	8957	2293	1501	924	512	0	1999
Netherlands							
Antilles	Est.2500	Est.2200	Est.1800	Est.1400	Est.1000	Est.600	No Date
Nicaragua	Est.150	Est.150	Est.150	Est.90	0	0	1996
Panama	Est.500	Est.500	Est.500	Est.500	Est.500	Est.500	-
Paraguay	93.6	67.2	86.1	187.6	Est.80	Est.80	No Date
Peru	1500	1450	1413	1149	1134	1159	No Date
Trinidad & Tobago	Est.75	46	23	23	8	8	2000
Uruguay	380	406	410	410	410	410	No Date
Venezuela	4783	4221	3637	3160	2870	2853	2007
TOTALS	27440	16403	13167	10259	7650	6428	
No. of countries contributing to total	20	18	17	16	12	11	
% of 1990 value	100	59.8	48.0	37.4	27.8	23.4	
No. of countries contributing to total	20	18	17	16	12	11	

N/D = No data

Est. = Estimate by Alconsult



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