“Supporting the Implementation of Lower Sulfur Fuels in China, P. R. for Environmental Protection” Project

A Handbook on Low Sulfur Fuels in China

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About the Author

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Contents

Introduction

Over approximately the last twenty-five years, extensive studies have been carried out to better establish the linkages between fuels and vehicles and vehicle emissions. One major study, the Auto/Oil Air Quality Improvement Research Program (AQIRP) was established in 1989 in the US and involved 14 oil companies, three domestic automakers and four associate members.[1] Likewise, in June 1993, a contract was signed by the auto and petroleum industries to undertake a common test program, called the European Program on Emissions, Fuels and Engine Technologies (EPEFE). In Asia, the Japan Clean Air Program (JCAP) was conducted by Petroleum Energy Center as a joint research program of the automobile industry (as fuel users) and the petroleum industry (as fuel producers), supported by the Ministry of Economy, Trade and Industry.[2] The second phase of the program focused on future automobile and fuel technologies aimed at realizing Zero Emissions while at the same time improving fuel consumption, with a special focus on studies of fine particles in exhaust emissions.

The most important lesson learned and reinforced from these studies is that with regards to vehicle emissions, **vehicles and fuels are a system** and need to be treated as such. A clear example of this reality is the close linkage between the requirement for lead-free gasoline as a precondition for the introduction of catalytic converter technology to reduce the carbon monoxide, hydrocarbons and nitrogen oxides which would otherwise be emitted in large quantities from gasoline-fueled vehicles. The more current example is the necessity of lowering levels of sulfur in gasoline and diesel fuel to enable the use of certain advanced pollution control technologies; in fact it is now understood that sulfur levels must be reduced to near zero if the **maximum** benefits are to be achieved by the most advanced technologies used with combustion engines today.

Relying heavily on each of these studies as well as other recent work, this handbook will summarize what is known about the impact of fuel sulfur content on vehicle emissions and to assess the implications for the phase-in of tighter new vehicle standards in China. The next section will summarize in general the impact of various gasoline and diesel fuel parameters on vehicle emissions as a function of the emissions standards that the affected vehicles are designed to meet. This will be followed by a summary of the fuel specifications adopted by the European Union, the United States and California as well as the specifications recommended by the Worldwide Fuels Charter. Finally, the paper will discuss the importance of low sulfur fuels for China and the implications for phasing in more stringent new vehicle standards.

Gasoline Vehicles and Fuels

A. General Description of Gasoline Fuel Parameters

Gasoline is a complex mixture of volatile hydrocarbons used as a fuel in internal combustion engines. The pollutants of greatest concern from gasoline-fuelled vehicles are CO, HC, NO_x, and certain toxic hydrocarbons such as benzene, formaldehyde, acetaldehyde, and 1,3-butadiene. Each of these can be influenced by the composition of the gasoline used by the vehicle. The most important characteristics of gasoline with regard to its impact on emissions are sulfur concentration, volatility, aromatics, olefins, oxygenates, and benzene level.

B. Impact of Gasoline Composition on Vehicle Emissions

Table A summarizes the impacts of various gasoline fuel qualities on emissions from light duty gasoline vehicles as a function of emissions standards.

C. Two and Three Wheeled Vehicles

China has a much larger population of two and three wheeled vehicles than anywhere else in the world. While emissions from these vehicles **are expected to be influenced by fuel characteristics**, there has been very little study focused on the impacts of specific fuel parameters on these vehicles. However, based on the limited available data and the combustion similarities between these and other internal combustion engines, these impacts are estimated as shown in Table B.

Table A. Impact of Gasoline Composition on Emissions from Light Duty Vehicles

Gasoline	No Catalyst	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5/6[3]	Comments
Lead ↑	Pb, HC↑	CO, HC, NO_x all increase dramatically as catalyst destroyed					Lead is banned in China gasoline since 2000
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NO_x all increase ~15-20% SO_2 and SO_3 increase					Onboard Diagnostic light may come on incorrectly
Olefins ↑	Increased 1,3 butadiene, increased HC reactivity, NO_x, small increases in HC for Euro 3 and cleaner						Potential deposit buildup
Aromatics ↑	Increased benzene in exhaust						Deposits on intake valves and combustion chamber tend to increase
	Potential increases in HC, NO_x	HC↑, NO_x↓, CO↑		HC, NO_x, CO ↑			
Benzene ↑	Increased benzene exhaust and evaporative emissions						
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NO_x increase(when above 2% oxygen content), Higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Concerns over water contamination
Distillation Characteristics T50, T90↑	Probably HC↑	HC↑					
MMT ↑	Increased Manganese Emissions			Possible Catalyst Plugging	Likely Catalyst Plugging		O_2 sensor and OBD may be damaged, MIL light may come on incorrectly
RVP ↑	Increased evaporative HC Emissions						Most critical parameter for Asian countries because of high ambient Temperatures
Deposit control additives ↑		Potential HC, NO_x emissions benefits					Help to reduce deposits on fuel injectors, carburetors, intake valves, combustion chamber

Notes: CO = carbon monoxide; HC = hydrocarbon; Pb = lead; RVP = Reid vapor pressure; MMT = methylcyclopentadienyl manganese tricarbonyl; MTBE = methyl tert-butyl ether; NO_x = oxides of nitrogen; O_2 = oxygen; SO_2 = sulfur dioxide; T50 = temperature at which 50% of the gasoline distils; T90 = temperature at which 90% of the gasoline distils

Table B. Impact of Gasoline Composition on Emissions from Motorcycles

Gasoline	No Catalyst	India 2005	Euro 3	India 2008	China Stage 3	Comments
Lead ↑	Pb, HC↑	CO, HC, NO_x all increase dramatically as catalyst destroyed				
Sulfur ↑ (50 to 450 ppm)	SO_2 ↑	CO, HC, NO_x all increase SO_2 and SO_3 increase				
Olefins ↑	Increased 1,3 butadiene, HC reactivity and NO_x					Potential deposit buildup
Aromatics ↑	Increased benzene exhaust					
Benzene ↑	Increased benzene exhaust and evaporative emissions					
Ethanol ↑ up to 3.5% O_2	Lower CO, HC, slight NO_x increase	Minimal effect with oxygen sensor equipped vehicles				Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O_2	Lower CO, HC	Minimal effect with O_2 sensor equipped vehicles				Concerns over Water Contamination small fuel economy penalty
Distillation characteristics T50, T90 ↑	Probably HC↑	HC↑				Not as quantifiable as in passenger cars
MMT ↑	Increased Manganese Emissions	Possible Catalyst Plugging				With low cell density, catalyst plugging risk seems small but there are concerns regarding deposits on spark plugs and in the combustion chamber
RVP ↑	Increased evaporative HC Emissions					
Deposit control additives ↑		Potential emissions benefits				Help to reduce deposits on fuel injectors, carburetors

Notes: CO = carbon monoxide; HC = hydrocarbon; Pb = lead; RVP = Reid vapor pressure; MMT = methylcyclopentadienyl manganese tricarbonyl; MTBE = methyl tert-butyl ether; NO_x = oxides of nitrogen; O_2 = oxygen; SO_2 = sulfur dioxide; T50 = temperature at which 50% of the gasoline distils; T90 = temperature at which 90% of the gasoline distils

Most two- and three-wheeled vehicles currently used in China are not equipped with catalytic converters to control emissions. Therefore it would seem that the impact of the various fuels parameters will be similar to those from pre Euro 1 cars. Since China III limits have been introduced however, vehicles are impacted by sulfur and lead in a manner similar to Euro 1 and 2 gasoline fueled cars. For two- and three-wheeled vehicles equipped with 2-stroke engines, the amount and quality of the lubricating oil is probably more important for emissions than fuel quality but this technology is rapidly being phased out in China.

Diesel Vehicles and Fuels

A. General Description of Diesel Fuel Parameters

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

Diesels emit high levels of oxides of nitrogen and particulates. Modest to significant NO_x control can be achieved by delaying fuel injection timing and adding exhaust gas recirculation (EGR). Very high pressure, computer controlled fuel injection can also be timed to reduce PM emissions. Modifying engine parameters to simultaneously reduce both NO_x and PM is difficult and limited since the optimal settings for one pollutant frequently increases emissions of the other and vice-versa. Achieving very low levels of NO_x and PM therefore requires exhaust treatment. Lean NO_x catalysts, selective catalytic reduction (SCR), NO_x storage traps with periodic reduction, filter traps with periodic burn-off, and oxidation catalysts with continuous burn-off are evolving technologies that are being phased in at differing rates in various parts of the world.

Reformulated diesel fuels can effectively reduce oxides of nitrogen and particulate emissions from all diesel vehicles. These fuels have reduced sulfur, reduced aromatics, and increased cetane number. To reduce PM and NO_x emissions from a diesel engine, the most important fuel characteristic is sulfur because sulfur contributes directly to PM emissions and high sulfur levels preclude the use of or impair the performance of the most effective PM and NO_x control technologies.

B. Impact of Diesel Fuel Composition on Vehicle Emissions[4]

The following tables (C and D) summarize the impacts of various diesel fuel qualities on emissions from light and heavy duty diesel vehicles, respectively.

Table C. Impact of Fuels on Light Duty Diesel Vehicles

Diesel Fuel Characteristic	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5/6[5]	Comments
Sulfur↑	SO_2, PM↑		If oxidation catalyst is used, SO_3, SO_2, PM↑		If Filter, 50 ppm maximum, 10-15 ppm better		If NO_x adsorber used requires near zero sulfur (<10 ppm) With low S, use lubricity additives
Cetane↑	Lower CO, HC, benzene, 1,3 butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels
Density↓	PM, HC, CO, formaldehyde, acetaldehyde & benzene↓, NO_x↑						
Volatility (T95 from 370 to 325 C)	NO_x, HC increase, PM, CO decrease						
Polyaromatics↓	NO_x, PM, formaldehyde & acetaldehyde↓ but HC, benzene & CO ↑						Some studies show that total aromatics are important for emissions in a manner similar to polyaromatics

Notes: CO = carbon monoxide; HC = hydrocarbon; NO_x = oxides of nitrogen, PM = particulate matter; ppm = parts per million; SO_2 = sulfur dioxide; SO_3 or sulfur trioxide is an intermediate compound.

Table D. Impact of Fuels on Heavy Duty Diesel Vehicles

Diesel	Pre-Euro	Euro I	Euro II	Euro III	Euro IV	Euro V[6]	Comments
Sulfur↑	SO_2, PM↑		If oxidation catalyst is used, SO_3, SO_2, PM↑		If Filter, 50 ppm maximum, 10-15 ppm better		If NO_x adsorber used requires near zero sulfur (<10 ppm) With low S, use lubricity additives
Cetane↑	Lower CO, HC, benzene, 1,3-butadiene, formaldehyde & acetaldehyde						Higher white smoke with low cetane fuels
Density↓	HC, CO ↑, NO_x↓						
Volatility (T95 from 370 to 325 C)	Slightly lower NO_x but increased HC						Too large a fraction of fuel that does not volatilize at 370 C increases smoke and PM
Polyaromatics↓	NO_x, PM, HC ↓						Some studies show that total aromatics are important

Notes: CO = carbon monoxide; HC = hydrocarbon; NO_x = oxides of nitrogen, PM = particulate matter; ppm = parts per million; S = sulfur; SO_2 = sulfur dioxide; SO_3 or sulfur trioxide is an intermediate compound

The EU, US and California Fuel Specifications

In response to the various studies relating vehicle technologies to fuels, various countries have modified their fuel quality specifications. Table E summarizes the European Union, US EPA and California Air Resources Board specifications and recommendations from the Worldwide Fuel Charter.

Table E. Selected Gasoline Specifications

	Euro 3	Euro 4	Euro 5	EPA RFG average (2005)[7]		EPA conv. gasoline average (2005)[8]		CARB[9] (CaRFG3)			Worldwide Fuel Charter Category 4[10]
				Summer	Winter	Summer	Winter	Flat limits	Averaging limits	Cap limits	
Aromatics, vol%, max	42	35	35	20.7[11]	19.5[11]	27.7	24.7	25	22	35	35
Olefin, vol%, max	18	18	18	11.9	11.2	12	11.6	6	4	10	10
Benzene, wt.%, max	1	1	1	0.66[12]	0.66[12]	1.21[12]	1.15[12]	0.8	0.7	1.1	1
Sulfur, ppm, max	150	50	10	71[13]	81[13]	106[13]	97[13]	20	15	30 20[14]	10
RVP, kPa	60/70 max	60/70 max	60/70 max	47.6[15] (6.91 psi) max	82.0 (11.89 psi) max	57.2[16] (8.3 psi)	83.6 (12.12 psi)	48.2 or 47.6[17] max (7 or 6.9 psi)	NAP	44.1-49.6 (6.4-7.2 psi)	Same as proposed China IV
Manganese, mg/liter	NS	NS	MMT<6 (by 2011) MMT<2 (by 2014)	NA[18]	NA[19]	NA	NA	ND	ND	ND	ND
Oxygen, % m/m	2.7 (max)	2.7 (max)	2.7 (max)	2.49	2.37	0.95	1.08	1.8-2.2	NAP	0 - 3.5 1.8[20] - 3.5	2.7

NS = Not specified; NA = Not available; ND = Non-detectable; NAP = Not applicable

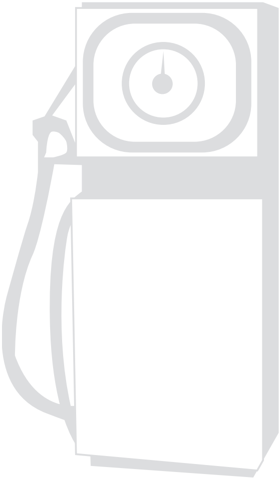
Recently the US has made a formal proposal to further tighten its gasoline sulfur specification as well as vehicle emissions standards. When finalized, sulfur levels will be lowered from the current average of 30 to 10 ppm.

Table F summarizes similar specifications for diesel fuel.

Table F. Selected Diesel Specifications

	Euro III	Euro IV	Euro V	EPA	CARB		Worldwide Fuel Charter Category 4 [21]
				Conventional diesel	Reference fuel [22]	Designated equivalent limit [23]	
Polyaromatics, vol%, max	11	11	8	NS	1.4	3.5	2.0
Sulfur, ppm, max	350	50	10	15	15	15	10
Cetane number, min	51	51	51	Cetane index ≥ 40 or aromatics ≤ 35%[24]	48	53	55
Density @ 15°C, kg/m^3, min	820 - 845	845	845	NS	NS	NS	820 [25]
Flash point, °C, min	55	Same as Euro III	Same as Euro III	NS	54	NS	55
Ash content, % m/m, max	0.01	Same as Euro III	Same as Euro III	NS	NS	NS	0.001
Viscosity @ 40°C, mm^2/s	2 - 4.5	Same as Euro III	Same as Euro III	NS	2 - 4.1	NS	2.0 [26]

PP = Diesel pour point; NS=Not specified



Why The World is Moving Toward Near Zero Sulfur Levels in Fuels

A. Background

Both petrol and diesel fuels are produced from crude oil, which varies from oilfield to oilfield in color and composition. Crude oils range in consistency from water to tar-like solids, and in color from clear to black. An “average” crude oil contains about 84% carbon, 14% hydrogen, 1%-3% sulfur, and less than 1% each of nitrogen, oxygen, metals, and salts.[27] However, crude oil is of little use in its raw state; its value lies in what is created from it when distilled – fuels, lubricating oils, waxes, asphalt, and petrochemicals.

Sulfur, a non-metallic element, is widely found in nature and occurs naturally in crude oil. The amount of sulfur in crude oil can range anywhere from 100 to 33,000 parts per million (ppm)[28]. If a crude oil contains little or no sulfur it is called “sweet crude” (up to approximately 7,000 ppm), if it contains some sulfur it is called “medium sour (between 7,000 and 10,000 ppm) and if it contains considerable quantities of sulfur it is called “sour crude” (from 10,000 ppm up to 33,000 ppm or higher). Sulfur may be present in crude oil as hydrogen sulfide (H_2S), as compounds (e.g. mercaptans, sulphides, disulphides, thiophenes, etc.) or as elemental sulfur. When crude oil is processed into gasoline and diesel fuel in the refinery, some sulfur finds its way into the fuel. The higher the density of the crude oil, the more difficult it is to remove the sulfur. Depending on the crude oil used and the refinery configuration, sulfur levels in gasoline can be anywhere from 50 to as high as 1000 ppm or more, and in diesel fuel it can be from 15 or lower to more than 10,000 ppm.

B. Concerns about Sulfur

There are four main reasons why countries are concerned about the sulfur content of fuels:

a) Health Impacts
b) Other Environmental Impacts
c) Global Concerns: Climate Change
d) The Impact of Sulfur on Advanced Vehicle Pollution Control Technologies

a) Health Impacts

Motor vehicles can emit large quantities of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and such toxic substances as benzene, formaldehyde, acetylaldehyde, 1,3-butadiene and fine particles (PM) when they are operating. Depending on fuel composition, they can also emit significant amounts of sulfur oxides (SO_x) and lead. Each of these, along with secondary by-products such as ozone (O_3), can cause serious adverse effects on health and the environment. Greenhouse gases (GHGs) responsible for climate change are also increasingly emitted by the transportation sector. Vehicle emissions most closely identified with this sector include carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). However, it is important to note that other vehicle-related pollutants also contribute to global warming; this is especially true of black carbon which has recently received a great deal of attention as the scientific understanding of its role in climate change has increased.

Exposure to levels of air pollutants has been associated with a variety of adverse health effects. Based on available information, the World Health Organization (WHO) sets and periodically updates air quality guidelines. The following summary is based on the most recent guidelines adopted by the World Health Organization (WHO)[29] and standards adopted by the United States Environmental Protection Agency (US EPA).

- **Particulate Matter (PM)**

Particulate matter (PM) represents a broad class of chemically and physically diverse substances. It can be principally characterized as discrete particles that exist in the condensed (liquid or solid) phase spanning several orders of magnitude in size. PM_{10} refers to particles generally less than or equal to 10 micrometers (µm). Inhalable (or ''thoracic'') coarse particles refer to those particles generally larger than 2.5 µm but less than or equal to 10 µm in diameter. $PM_{2.5}$ refers to fine particles, those particles generally less than or equal to 2.5 µm in diameter. Ultrafine PM refers to particles less than 0.1 µm in diameter. Larger particles tend to be removed by the respiratory clearance mechanisms (e.g. coughing), whereas smaller particles are deposited deeper in the lungs, or even absorbed into the blood through the lungs.

Fine particles are produced primarily by combustion processes but also through transformations of gaseous emissions (e.g., SO_x, NO_x and VOCs) in the atmosphere. Thus, $PM_{2.5}$ includes a complex mixture of different pollutants including sulfates, nitrates, organic compounds, elemental carbon and metal (including toxic heavy metal) compounds. These particles can remain in the atmosphere for days to weeks and travel through the atmosphere hundreds to thousands of kilometers.

The range of effects of PM is broad, affecting the respiratory and cardiovascular systems and extending to children and adults and to a number of large, susceptible groups within the general population of developed and developing countries. Risk increases with exposure and there is little evidence to suggest a threshold below which no adverse health effects would be anticipated.

The WHO Air Quality Guidelines for PM are:

$PM_{2.5}$: 10 µg/m^3 annual mean, 25 µg/m^3 24-hour mean
PM_{10}: 20 µg/m^3 annual mean, 50 µg/m^3 24-hour mean

Health effects associated with short-term exposures (hours to days) to ambient PM include premature mortality, increased hospital admissions, heart and lung diseases, increased cough, adverse lower-respiratory symptoms, decrements in lung function and changes in heart rate rhythm and other cardiac effects. Studies examining populations exposed to different levels of air pollution over a number of years show associations between long-term exposure to ambient $PM_{2.5}$ and both total and cardiovascular and respiratory mortality.[30,31] In addition, a reanalysis of the American Cancer Society Study shows an association between **fine particle and sulfate concentrations and lung cancer mortality**.[32]

The health effects of $PM_{2.5}$ have been further documented in local impact studies which have focused on health effects due to $PM_{2.5}$ exposures measured on or near roadways. Taking account of all air pollution sources, including both spark-ignition (gasoline) and diesel-powered vehicles, these latter studies indicate that exposure to $PM_{2.5}$ emissions near roadways, dominated by mobile sources, are associated with potentially serious health effects. For instance, a recent study found associations between concentrations of cardiac risk factors in the blood of healthy young police officers and $PM_{2.5}$ concentrations measured inside vehicles.[33] Also, a number of studies have shown associations between residential or school outdoor concentrations of some constituents of fine particles found in motor vehicle exhaust and adverse respiratory outcomes, including asthma prevalence in children who live near major roadways.[34,35,36]

In addition to $PM_{2.5}$ and PM_{10}, ultra-fine particles (UF) have recently attracted significant scientific and medical attention. These are particles smaller than 0.1 micrometer and are measured as number concentration. While there is considerable toxicological evidence of potential detrimental effects of UF particles on human health, the existing body of epidemiological evidence is insufficient in the view of WHO to reach a conclusion on the exposure/response relationship to UF particles. Therefore no recommendations have yet been provided by the WHO as to guideline concentrations of UF particles at this point.

The Global Burden of Disease Study 2010 (GBD, 2010) is the largest-ever systematic effort to describe the global distribution and causes of a wide array of major diseases, injuries, and health risk factors.[37] The results show that outdoor air pollution, primarily $PM_{2.5}$ is responsible for over 3.2 million premature deaths each year, over 1.2 million of which occur in China. It is clear that air pollution is an extremely serious and widespread problem which requires strong action.

• Ozone (O_3)

Ground-level ozone pollution is formed by the reaction of VOCs and NO_x in the atmosphere in the presence of heat and sunlight.

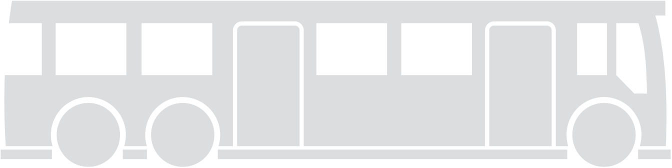
The health and welfare effects of ozone are well documented.[38,39] Ozone can irritate the respiratory system, causing coughing, throat irritation, and/ or uncomfortable sensation in the chest. It can reduce lung function and make it more difficult to breathe deeply, and breathing may become more rapid and shallow than normal, thereby limiting a person's activity. Ozone can also aggravate asthma, leading to more asthma attacks that require a doctor's attention and/or the use of additional medication. Animal toxicological evidence indicates that with repeated exposure, ozone can inflame and damage the lining of the lungs, which may lead to permanent changes in lung tissue and irreversible reductions in lung function. People who are more susceptible to effects associated with exposure to ozone include children, the elderly, and individuals with respiratory disease such as asthma. Those with greater exposures to ozone, for instance due to time spent outdoors (e.g., children and outdoor workers), are also of concern, even with short-term exposure under current ground-level ozone levels. [40] Current research suggests that the actual ozone concentration threshold for mortality may be lower than current public health standards, and research on this topic is ongoing. In light of variation of response of different individuals to ambient ozone levels, the WHO recommends that air quality guidelines be set at the level of:

Ozone: 100 μg/m^3 for daily maximum 8-hour mean

It should be noted that background concentrations of ground-level ozone vary in time and space but can reach average levels of around 80 μg/m^3. These arise from both anthropogenic and biogenic emissions of ozone precursors and downward intrusion of stratospheric ozone into lower levels of the atmosphere, and as a result, the proposed WHO guideline value may occasionally be exceeded due to natural causes.

• Nitrogen Dioxide (NO_2)

Evidence from animal toxicological studies indicates that long-term exposure to NO_2 at concentrations above current ambient concentrations has adverse effects. In population studies NO_2 has been associated with adverse health effects even when the annual average NO_2 concentration complied with the WHO-2000 annual guideline value of 40 μg/m^3. Also some indoor studies suggest effects on respiratory symptoms among infants at concentrations below 40 μg/m^3. Together these results support a lowering of the annual NO_2 guideline value. However,



NO_2 is an important constituent of combustion-generated air pollution and is highly correlated with other primary and secondary combustion products; it is unclear to what extent the health effects observed in epidemiological studies are attributable to NO_2 itself or to other correlated pollutants. The current scientific literature, therefore, has not accumulated sufficient evidence to change the WHO 2000 guideline value of 40 µg/m^3 for annual NO_2 concentrations.

Short-term experimental human toxicology studies show acute health effects at levels higher than 500 µg/m^3, and one meta-analysis has indicated effects at levels exceeding 200 µg/m^3. The current scientific literature has not accumulated evidence to change from the WHO 2000 guideline value of 200 µg/m^3 for 1-hour NO_2 concentration.

In conclusion, the WHO guideline values remain unchanged at the following levels:

NO_2 concentration: 40 µg/m^3 for annual mean;
NO_2 concentration: 200 µg/m^3 for 1-hour mean.

The California Air Resources Board approved staff recommendations to lowering the existing 1-hour-average standard for NO_2 of 0.25 ppm to 0.18 ppm, not to be exceeded, and established a new annual-average standard of 0.030 ppm, not to be exceeded.

Further evidence from recent studies is is “sufficient to infer a likely causal relationship” between short-term exposure to nitrogen dioxide and adverse effects on the respiratory system. According to a draft Environmental Protection Agency risk assessment, a 30-minute exposure to nitrogen dioxide concentrations between 0.2 ppm and 0.3 ppm has been shown to irritate airways in asthmatics. Children, whose lung function continues to develop into adolescence, and those over the age of 65 are also particularly susceptible to nitrogen dioxide exposure. The risk assessment also identified as an at-risk group those whose jobs require significant periods of driving. Mean nitrogen dioxide levels inside vehicles are often two to three times the outdoor concentrations.

• Sulfur Dioxide (SO_2)

Controlled short-term exposure studies with exercising asthmatics indicate that some individuals experience changes in pulmonary function and respiratory symptoms after periods of exposure as short as 10 minutes. Based on this evidence, it is recommended by WHO that a value of **500 µg/m^3** should not be exceeded over **averaging periods of 10 minutes**. Because exposure to sharp peaks depends on the nature of local sources and meteorological conditions, no single factor can be applied to this value in order to estimate corresponding guideline values over somewhat longer periods, such as an hour.

For longer-term exposure, there is still considerable uncertainty as to whether sulfur dioxide is the pollutant responsible for the observed adverse effects or, rather, a surrogate for ultra-fine particles or some other correlated substance. For example, in Germany[41] and the Netherlands[42] a strong reduction of SO_2 concentrations occurred over a decade. Although mortality also decreased with time, the association of SO_2 and mortality was judged to not be causal and was attributed to a similar time trend of a different pollutant (PM). In consideration of: (1) the uncertainty of SO_2 in causality; (2) the practical difficulty of reaching levels that are certain to be associated with no effects; and (3) the need to provide greater degrees of protection than those provided by the guidelines published in 2000, and assuming that reduction in exposure to a causal and correlated substance is achieved by reducing sulfur dioxide concentrations, then there is a basis for revising the 24 hour guideline downward for sulfur dioxide, and the following guideline is recommended as a prudent precautionary level:

Sulfur dioxide: 20 $\mu g/m^3$ for 24-hour mean.
500 $\mu g/m^3$ for 10-minute mean (unchanged)

The WHO has determined that an annual guideline is not needed, since compliance with the 24-hour level will assure low levels for the annual average.

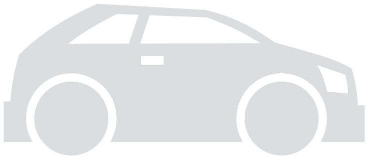
• Carbon Monoxide (CO)

Carbon monoxide – an odorless, invisible gas created when fuels containing carbon are burned incompletely – also poses a serious threat to human health. Fetuses and persons afflicted with heart disease are especially at risk. 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.[43] Some recent epidemiologic studies have found relationships between increased CO levels and increases in mortality and morbidity.[44]

Healthy individuals also are affected, but only at higher levels. Exposure to elevated CO levels is associated with impairment of visual perception, work capacity, manual dexterity, learning ability and performance of complex tasks.

• Air Toxics

People experience elevated risk of cancer and other noncancerous health effects from exposure to air toxics. Mobile sources are a major source of this exposure. According to the US National Air Toxic Assessment (NATA) for 1999, mobile sources were responsible for 44 percent of outdoor toxic emissions and almost 50 percent of the cancer risk among the 133 pollutants quantitatively assessed. Benzene is the largest contributor to cancer risk of all the assessed pollutants and mobile sources were responsible for about 68 percent of all benzene emissions in 1999.



According to the 1999 NATA, nearly the entire U.S. population was exposed to an average level of air toxics that has the potential for adverse respiratory noncancerous health effects.[45] Mobile sources were responsible for 74 percent of the potential noncancerous hazard from outdoor air toxics. It is important to note that NATA estimates of noncancerous hazard do not include the adverse health effects associated with particulate matter.

b) Other Environmental Effects

There are a number of public welfare effects associated with the presence of ozone and $PM_{2.5}$ in the ambient air including the impact of $PM_{2.5}$ on visibility and materials and the impact of ozone on plants, including trees, agronomic crops and urban ornamentals.

- **Visibility**

Visibility can be defined as the degree to which the atmosphere is transparent to visible light. Visibility impairment manifests in two principal ways: as local visibility impairment and as regional haze.[46] Local visibility impairment may take the form of a localized plume, a band or layer of discoloration appearing well above the terrain as a result of complex local meteorological conditions. Alternatively, local visibility impairment may manifest as an urban haze. This urban haze is largely caused by emissions from multiple sources in the urban areas and is not typically attributable to only one nearby source or to long-range transport. The second type of visibility impairment, regional haze, usually results from multiple pollution sources spread over a large geographic region. Regional haze can impair visibility in large regions and across states.[47,48]

- **Acid Deposition**

Acid deposition, or acid rain as it is commonly known, occurs when NOx and SO_2 react in the atmosphere with water, oxygen and oxidants to form various acidic compounds that later fall to earth in the form of precipitation or dry deposition of acidic particles. It contributes to damage of trees at high elevations and in extreme cases may cause lakes and streams to become so acidic that they cannot support aquatic life. In addition, acid deposition accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of a nation's cultural heritage.

Nitrogen oxides have also been found to contribute to ocean acidification, thereby amplifying one of the many deleterious impacts of climate change.[49] Approximately one third of all nitrogen oxide emissions end up in the oceans. The impact of these emissions on acidification is intensely felt in specific, vulnerable areas; in some areas it can be as high as 10 to 50 percent of the impact of carbon dioxide. The hardest hit areas are likely to be those directly around the release site, so these emissions are especially significant in and around coastal waters.

• Eutrophication and Nitrification

Eutrophication is the accelerated production of organic matter, particularly algae, in a water body. Nitrogen deposition contributes to eutrophication of watersheds, particularly in aquatic systems where atmospheric deposition of nitrogen represents a significant portion of total nitrogen loadings. This increased growth can cause numerous adverse ecological effects and economic impacts, including nuisance algal blooms, dieback of underwater plants due to reduced light penetration, and toxic plankton blooms. Algal and plankton blooms can also reduce the level of dissolved oxygen, which can adversely affect fish and shellfish populations. In recent decades, human activities have greatly accelerated nutrient impacts, such as nitrogen and phosphorus, causing excessive growth of algae and leading to degraded water quality and associated impairment of freshwater and estuarine resources for human uses.[50]

Severe and persistent eutrophication often directly impacts human activities. For example, losses in a nation's fishery resources may be directly caused by fish kills associated with low dissolved oxygen and toxic blooms. Declines in tourism occur when low dissolved oxygen causes noxious smells and floating mats of algal blooms create unfavorable aesthetic conditions. Risks to human health increase when the toxins from algal blooms accumulate in edible fish and shellfish, and when toxins become airborne, causing respiratory problems due to inhalation.

c) Global Concerns: Climate Change

There is no longer any scientific dispute that human production of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are responsible for the unprecedented rate of warming observed over the past century. According to the Intergovernmental Panel on Climate Change ("IPCC"), "Warming of the climate system is unequivocal, as is now evident from observations of increases in global air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."[51]

Moreover, "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Thus, the world's leading scientific body on the subject has now concluded, with greater than 90 percent certainty, that emissions of greenhouse gases are responsible for climate change. In addition to these three mentioned greenhouse gases, black carbon, a fraction of PM, is a significant climate forcing pollutant.

• Black Carbon (BC)

A product of inefficient combustion, black carbon, also known as soot, consists of microscopic solid particles of incompletely burned organic matter.[52] Black carbon is a potent warmer, exerting effects on the global climate both while suspended in the atmosphere and when deposited on snow and ice. In fact, one study estimates that a given mass of black carbon will warm the air between 360,000 and 840,000 times more than an equal mass of carbon dioxide.[53] While the quantification is quite variable, a large number of recent studies have raised serious concerns regarding the climate impacts of black carbon.[54] The most pernicious characteristic of black carbon from a climatic perspective is its dark color and correspondingly low albedo, or reflectivity. Because of this dark coloring, black carbon absorbs heat from sunlight.

A very recent study[55] finds that soot is warming the climate about twice as fast as scientists had estimated.[56] The new, deeper view puts soot second behind the dominant agent forcing warming, carbon dioxide, which accounts for 1.66 W/m^2. Soot's contribution to the warming is roughly twice as large as estimated in the 2007 assessment made by the Intergovernmental Panel on Climate Change.

d) The Impact of Sulfur on Advanced Vehicle Pollution Control Technologies

While sulfur contributes to adverse effects on both health and the environment in a number of ways, the most important concern with regard to vehicle emissions is the impact on pollution control technology. The primary reason for introducing lower sulfur vehicle fuels, therefore, is to enable the introduction of emissions control devices that can significantly reduce vehicle emissions and to allow them to achieve their full emissions reduction potential. These technologies are already in place in some countries and are continuously being improved to further control vehicle emissions. However, these technologies generally require specific fuel qualities, often including low sulfur levels.

i. Sulfur in Gasoline

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

Modern gasoline engines use computer controlled intake port fuel injection with feedback control based on an oxygen sensor to meter precisely the quantity and timing of fuel delivered to the engine. Control of in-cylinder mixing and use of high-energy ignition promote nearly complete combustion. The three-way catalyst provides greater than 90% reduction of carbon monoxide, hydrocarbons, and oxides of nitrogen. Designs for rapid warm-up minimize cold-start emissions. On-board diagnostic (OBD) systems sense emissions systems performance and

identify component failures. Durability in excess of 160,000 km, with minimal maintenance, is now common.

Three-way catalytic converters were introduced on cars in the United States and Japan well before the impact of sulfur on catalyst performance was fully understood. We now know that sulfur in gasoline reduces the efficiency of catalysts and adversely affects heated exhaust gas oxygen sensors. High sulfur gasoline is a barrier to the introduction of new lean burn technologies using De-NO_x catalysts, while low sulfur gasoline will enable new and future conventional vehicle technologies to realize their full benefits. If sulfur levels are lowered, existing vehicles equipped with catalysts will generally have improved emissions.

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

The EPEFE study demonstrated the relationship between reduced gasoline sulfur levels and reductions in vehicle emissions. It found that reducing sulfur in fuel reduced exhaust emissions of HC, CO and NO_x (The effects were generally linear at around 8-10% reductions as fuel sulfur was reduced from 382 ppm to 18 ppm).[57] The study results confirmed that fuel sulfur affects catalyst efficiency with the greatest effect being in the warmed-up mode. In the case of air toxins, benzene and C3-12 alkanes were in line with overall hydrocarbon reductions, with larger reductions (around 18%) for methane and ethane.

For gasoline-fueled vehicles with no catalytic converters, reducing sulfur will have no effect on the pollutants of greatest concern, CO, HC or NO_x. While the amount of SO_2 emitted is in direct proportion to the amount of sulfur in the fuel, gasoline vehicles are not usually a significant source of SO_2. Since SO_2 can be converted in the atmosphere to sulfates, however, these emissions will also contribute to ambient levels of particulate matter (PM_{10} and $PM_{2.5}$) which is an increasingly serious concern in Chinese cities.[58]

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

Based on the experience with advanced gasoline fueled vehicle emissions controls, it is concluded that vehicles meeting both Euro 5 and Euro 6 emissions standards can perform satisfactorily with gasoline having a maximum sulfur content of 50 ppm. If and when they shift to 10 ppm maximum sulfur fuels, their performance will improve.

ii. Sulfur in Diesel Fuel

The contribution of the sulfur content of diesel fuel to exhaust particulate emissions has been well established with a general linear relationship between fuel sulfur levels and this regulated emission. Shown below (Figure 1) is one estimate of this relationship calculated from data provided by the US EPA (This figure shows only the sulfur-related PM and not the total PM emitted from a diesel engine). An indirect relationship also exists as some emissions of sulfur dioxide will eventually be converted in the atmosphere to sulfate PM.[59]

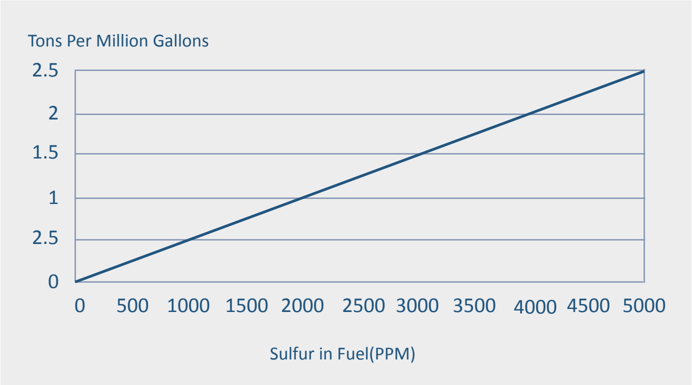


Figure 1. Tons of Directly Emitted PM from Diesel Fuels Sulfur

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

For diesel vehicles with no controls, the amount of sulfur in the fuel is directly related to SO_2 and PM emissions. Figure 2 illustrates the linkage between sulfur levels in the fuel and the mass of particulate; sulfur sits on the surface of the carbonaceous core in direct proportion to the amount of sulfur in the fuel.

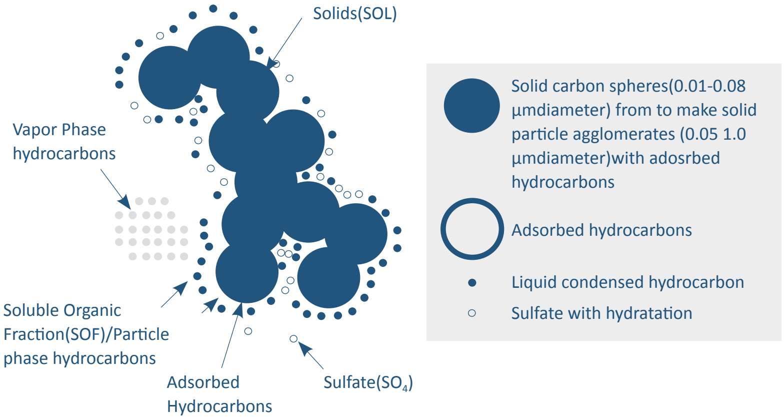


Figure 2. Schematic Illustration of a Typical Diesel Particle

Source: Health Effects Institute (HEI)

The amount of SO_3 emissions is also directly proportional to the amount of sulfur contained in the fuel. In the oxygen-rich exhaust of diesel vehicles several percent of the SO_2 formed during combustion is oxidized to SO_3, which dissolves in the water vapor present to form sulfuric acid (H_2SO_4) vapor. H_2SO_4 forms very small (so called ultrafine) particles in diesel exhaust which are considered especially hazardous because of their ability to penetrate deeply into the lungs. Even though sulfate particles account for only a small fraction of particle volume or mass, they account for a large fraction of particle numbers.

According to the US EPA, approximately 2% of the sulfur in the diesel fuel is converted to direct PM emissions. In addition, SO_2 emissions can lead to secondary particle formation-particles that form in the ambient air. US EPA models predict that over 12% of the SO_2 emitted in urban areas is converted in the atmosphere to sulfate PM. Urban areas would benefit most from reductions in SO_2 emissions, as polluted urban air has higher concentrations of the constituents that catalyze the SO_2-to-sulfate reaction. Even with vehicle stocks without advanced pollution controls, reductions of fuel sulfur levels would likely have a significant impact on primary and secondary PM concentrations in urban areas.

• Impact of Sulfur on Diesel Oxidation Catalysts

Light duty diesel engines (<3.5 tons gross vehicle weight (GVW)) generally require diesel oxidation catalysts (DOCs) to comply with Euro II or more stringent vehicle emission standards.

Oxidation catalysts lower hydrocarbons, carbon monoxide and particle emissions, typically removing around 30% of total particle mass emissions through oxidation of a large proportion of the soluble organic fraction. The conversion of sulfur in the catalyst reduces the availability of active sites on the catalyst surface and therefore reduces catalyst effectiveness.

However, the effectiveness of DOCs is dramatically reduced by sulfur in diesel fuel, and therefore they should be used only in areas which have fuel sulfur levels of 500 ppm or below.

• Impact of Sulfur on Diesel Particulate Filters

Diesel particulate filters (DPFs) reliably demonstrate over 95% efficiency in removing PM from diesel exhaust with near-zero sulfur fuel use. They are also capable of reducing the total **number** of particles emitted to levels similar to or even slightly lower than those of gasoline engines. Filters however need to be cleaned, ideally without human intervention, before reaching capacity in order to maintain vehicle performance and fuel and filter efficiency.

The Continuously Regenerating Diesel Particulate Filter (CR-DPF) and the Catalyzed Diesel Particulate Filter (CDPF) are two examples of PM control with passive regeneration, not requiring human intervention. The CR-DPF and CDPF devices were found to achieve 95% efficiency for control of PM emissions with 3 ppm sulfur fuel.[60] Efficiency dropped to zero with 150 ppm sulfur fuel and PM emissions more than double over the baseline with 350 ppm sulfur fuel. The increase in PM mass comes mostly from water bound to sulfuric acid. Soot emissions also increase with higher sulfur fuel but even with the 350 ppm sulfur fuel DPFs maintain around 50% efficiency for non-sulfate PM. With 50 ppm sulfur fuel, advanced PM filters can work satisfactorily – more than 75% reduction of $PM_{2.5}$ and smaller particles - although not as well as with 10 ppm sulfur. The systems recover to original PM control efficiency, over 95% with a shift to use of near-zero sulfur fuels, but recovery takes time due to sulfate storage on the catalyst.

As noted by TERI in a study of PM filters and low-sulfur fuel in Mumbai, "Continuously Regenerating Technology (CRT^{TM}) proved to be highly effective in reducing PM emissions from Ultra Low Sulfur Diesel (ULSD)-powered BS-II (approximately Euro II) buses. [61] It is, however, important to highlight that CRT is very sensitive to the sulfur content in diesel. According to Johnson Matthey, its manufacturer, a CRT can work effectively only if it is used in a modern diesel bus running on diesel of not more than 50 ppm sulfur–diesel or ULSD.

Sulfur also increases the required temperature for regeneration of the filter, meaning that more fuel is required in order to regenerate the filter. In moving from 3 to 30 ppm sulfur fuel, the exhaust temperatures required for regeneration increase by roughly 25°C. The CDPF requires consistently higher temperatures but holds stable at fuels with sulfur content above 30 ppm, while the CR-DPF requires ever-increasing temperatures.

• Impact of Sulfur on SCR Technology and NOx Adsorbers

SCR has emerged as the leading NO_x reduction technology. SCR uses a reducing agent, injected into the exhaust gas before the catalyst, to achieve high rates of NO_x conversion in the oxygen-rich exhaust.[62] Sulfur does not reduce conversion efficiency in SCR systems as directly as in other advanced control technologies, but emissions are impacted in a couple of ways. Fuel sulfur will increase the PM emissions from the downstream oxidation catalyst, and Sulfur reactions in urea-based SCR systems can also form ammonium bi-sulfate, a respiratory irritant.

NO_x adsorbers are also known as NO_x storage catalysts or lean NO_x traps. NO_x adsorber systems are still under development; they have demonstrated 95% efficiency in conversion of NO_x to N_2, with a nominal fuel penalty of 1.5%. However, long-term durability remains an issue. Also, without significant technological breakthroughs, it is generally recognized that this system can only operate with near zero sulfur fuels.

• Impact of Sulfur on Engine Durability

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

Diesel fuel has natural lubricity properties from compounds including the heavier hydrocarbons and organo-sulfur. Diesel fuel pumps (especially rotary injection pumps in light duty vehicles), without an external lubrication system, rely on the lubricating properties of the fuel to ensure proper operation. Refining processes to remove sulfur and aromatics from diesel fuel tend to also reduce the components that provide natural lubricity. In addition to excessive pump wear and, in some cases, engine failure, certain modes of deterioration in the injection system could also affect the combustion process, and hence emissions. Additives are available to improve lubricity with very low sulfur fuels and should be used with any fuels with 50 ppm sulfur or less.

Based on the experience with advanced diesel fueled vehicle emissions controls, it is concluded that light- and heavy- duty vehicles meeting both Euro 5 and Euro 6 emissions standards can perform satisfactorily with fuels having a maximum sulfur content of 50 ppm. If and when they shift to 10 ppm maximum sulfur fuels, their performance will improve.

Vehicle Emissions Standards Roadmap for China

China's Ministry of Environmental Protection (MEP) is currently wrestling with very difficult issues regarding the vehicle emissions standards roadmap for the remainder of this decade. On the one hand, MEP faces the most serious air pollution related health problems in the world with record high levels of ambient particulate and worsening ozone problems causing in excess of a million premature deaths each year. At the same time the vehicle manufacturing industry has become the largest in the world and an important pillar of economic growth. Therefore decisions made in the near future will have important implications for China's environment and economy.

The decision takes place in a context where China is already facing great difficulty achieving the NOx emissions reduction targets contained in the 12th Five Year Plan; instead of a reduction, NO_X emissions from the transportation sector increased by 7% between 2010 and 2012.

A. Analysis

This analysis focused on the emissions of $PM_{2.5}$, NO_X and Black Carbon over the 10-year lifetime from all new cars, trucks and buses to be sold in the 7 years from 2015 through 2021. In terms of new vehicle standards, five scenarios were investigated as summarized in Table G:

Table G. Potential Emissions Scenarios

	2015	2016	2017	2018	2019	2020	2021
China IV	China IV	China IV	China IV	China IV	China IV	China IV	China IV
China IV/V	China IV	China IV	China IV	China V	China V	China V	China V
China IV/V/VI	China IV	China IV	China IV	China V	China V	China V	China VI
China IV/VI	China IV	China IV	China IV	China VI	China VI	China VI	China VI
China V/VI	China V	China V	China V	China VI	China VI	China VI	China VI

The "China IV" scenario assumes that the current standard, China IV, is maintained with no further tightening between 2015 and 2021. "China V" assumes that China IV stays into effect until 2018 when China V is introduced. The assumption here is that China delays the introduction of China V until the nationwide fuel sulfur standard is a maximum of 10 ppm. "China IV/V/VI" is the same as China V except that three years after China V goes into effect in 2018, China VI[63] is mandated across the country.

"China IV/VI" is a scenario that skips China V entirely. Since 10 ppm sulfur will be in place across the country by the end of 2017, this case introduces China VI in 2018 since fuel quality would not be a problem. The last case, "China V/VI" is the most aggressive and is based on the conclusion that China V technology could work satisfactorily with 50 ppm fuel which will be mandated across the country in 2014.

New vehicles sales by model year and annual vehicle kilometers travelled were held constant for each emissions scenario. Vehicle lifetimes were limited to 10 years in all cases.

B. Results

Cumulative lifetime emissions[64] for the new vehicles sold in each of those seven years were estimated for each emissions scenario and are summarized in Table H.

Table H. Cumulative Lifetime Emissions from Model Years 2015-2021 New Vehicles (Tonnes)

	China IV	China V	China IV/V/VI	China IV/VI	China V/VI
$PM_{2.5}$	1,092,579	757,641	687,967	568,630	333,125
NO_x	24,752,689	20,688,152	18,781,152	16,338,779	13,544,023
BC	481,632	330,770	282,144	210,685	100,853

If there is no further tightening beyond the China IV standards currently in effect, over 1 million tons of $PM_{2.5}$, almost 25 million tons of NO_X and over 480,000 tons of Black Carbon are estimated to be emitted by Model Year 2015 through Model Year 2021 new vehicles over their lifetimes. If China V is introduced in 2018, emissions of $PM_{2.5}$, NO_X and BC could be reduced to ~750,000, 20 million and 330,000 tons, respectively. If in addition, China VI is then introduced in 2021, these emissions could be reduced to approximately 687,000, 18.8 million and 280,000, respectively. If instead of going to China VI in 2021, China V standards are skipped and replaced by China VI standards in 2018, overall emissions of $PM_{2.5}$, NOx and BC from these vehicles would drop to approximately 570,000, 16 million and 210,000 respectively. Finally, in the most stringent scenario considered, if China V were introduced in 2015 and China VI in 2018, overall emissions of $PM_{2.5}$, NO_X and BC could be reduced to approximately 333,000, 13.5 million and 100,000, respectively.

Tables I and J summarize the overall emissions reductions that could be achieved in both absolute and percentage terms from the seven model years under the other scenarios considered compared to the base case of staying with only China IV standards.

Table I. Emissions Reductions from Each Scenario Compared to the Base Case (Tonnes)

	China V	China IV/V/VI	China IV/VI	China V/VI
$PM_{2.5}$	334,938	404,612	523,949	759,454
NO_X	4,064,537	5,971,537	8,413,911	11,208,666
BC	150,862	199,488	270,947	380,779

Table J. Emissions Reduction from Each Scenario Compared to the Base Case (%)

	China V	China IV/V/VI	China IV/VI	China V/VI
$PM_{2.5}$	30.7%	37.0%	48.0%	69.5%
NO_X	16.4%	24.1%	34.0%	45.3%
BC	31.3%	41.4%	56.3%	79.1%

Introducing China V standards in 2015 and China VI in 2018 will reduce emissions of $PM_{2.5}$ by almost 70% compared to the base case and BC by almost 80%; in addition, NO_X emissions would be reduced by over 11 million tons, over 45% compared to the base case.

Conversely, staying with China IV until 2018 and only then switching to China V will only reduce $PM_{2.5}$ and BC by about 30% and NO_X by only 4 million tons. If China VI is added in 2021, the reduction in $PM_{2.5}$ and BC will rise to 37% and 41% respectively and the NO_X reduction would climb to almost 6 million tons.

Skipping China V completely and just going directly to China VI in 2018 seems to be an especially attractive option if concerns continue regarding the technical feasibility of introducing China V with 50 ppm sulfur fuel. This scenario would reduce $PM_{2.5}$ by just under 50%, BC by over 55% and eliminate almost 8.5 million tons of NO_X compared to the base case.

Looked at another way, each of the scenarios will emit much more $PM_{2.5}$, NOx and BC than would be emitted under the most stringent scenario. For example, if China V alone is introduced in 2018, almost 750,000 tons of excess $PM_{2.5}$ would be emitted; over 330,000 tons of BC and over 20 million tons of NO_X.

Table K. Excess Emissions Compared to Strongest Scenario (China V/VI) (Tonnes)

	China IV	China V	China IV/V/VI	China IV/VI
$PM_{2.5}$	1,076,779	741,841	672,167	552,830
NO_X	24,752,679	20,688,142	18,781,142	16,338,769
BC	481,632	330,770	282,144	210,685

Table L. Excess Emissions Compared to Strongest Scenario (China V/VI) (%)

	China IV	China V	China IV/V/VI	China IV/VI
$PM_{2.5}$	228%	127%	107%	71%
NO_x	83%	53%	39%	21%
BC	378%	228%	180%	109%

If China V were skipped and China VI introduced instead in 2018, the excess PM emission would drop to 550,000 tons, BC to 210,000 tons and NO_x to 16 million tons, still too much but much less than the other options. As shown in Tables M and N, substantial excess emissions would result from any of the other options.

Table M. Excess Emissions Compared to the Intermediate Scenario (China IV/VI) (Tonnes)

	China IV	China V	China IV/V/VI
$PM_{2.5}$	523,949	189,011	119,338
NO_x	8,413,911	4,349,374	2,442,374
BC	270,947	120,085	71,459

Table N. Excess Emissions Compared to the Intermediate Scenario (China IV/VI) (%)

	China IV	China V	China IV/V/VI
$PM_{2.5}$	92%	33%	21%
NO_x	51%	27%	15%
BC	129%	57%	34%

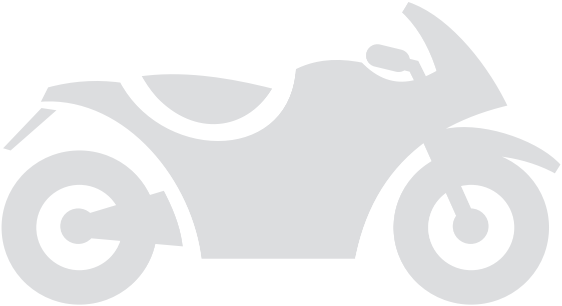
One message emerges loud and clear from this analysis – the quicker China can move to China VI standards, the better for the environment and the health of its citizens. With fuel sulfur levels to be realized at a maximum of 10 ppm by the end of 2017, there seems no reason to delay beyond 2018 for China VI vehicle emissions standards to be mandated. Introducing China V standards in 2015 after 50 ppm maximum sulfur content is in place across the entire country would provide significant additional benefits.

Concluding Remarks on Vehicles and Fuels

One of the most important lessons learned in the approximately 50-year history of vehicle pollution control worldwide is that vehicles and fuels must be treated as a system. Improvements in vehicles and fuels must proceed in parallel if significant improvements in vehicle related air pollution are to occur. A program that focuses on vehicles alone is doomed to failure; conversely, a program designed to improve fuel quality alone also will not be successful.

A second important lesson is that a program that focuses on cleaning up vehicles and fuels as a system can be successful. China is following the EU system for cleaning up vehicles and fuels and this system has laid out a clear roadmap which carefully links vehicle emissions standards and the associated technologies with appropriate fuel parameters and specifications needed to optimize emissions performance.

In light of the extremely serious air pollution problem facing China, the country must consider how rapidly it can accelerate its introduction of new vehicle standards now that the State Council has established a clean fuels road map.



Endnotes

1. "Auto/Oil Air Quality Improvement Research Program, Final Report", January 1997.
2. The program consisted of two stages: the first stage called JCAP I commenced in FY 1997 and terminated in FY 2001; the second called JCAP II commenced in FY 2002 and continued until 2007 to provide a further development of the research activities of JCAP I.
3. Euro 5 emissions standards were adopted for implementation in 2010; Euro 6 was adopted for 2014/2015 implementation.
4. China has linked its vehicle emissions control program to the EU or ECE requirements so much of the discussion that follows will relate fuels parameters to different technologies meeting EU standards.
5. Euro 5 emissions standards for light duty diesel vehicles have been adopted by the EU for implementation in 2010; Euro 6 limits were also adopted for 2015 implementation. Both Euro 5 and Euro 6 standards are expected to mandate the use of PM filters on all light duty diesel vehicles.
6. The EU Commission has adopted Euro VI emissions standards for heavy duty engines, likely mandating the use of PM filters on all heavy duty diesel vehicles from 2014.
7. National average of the 2005 RFG survey data are shown here. Even though EPA establishes limits on sulfur, summer RVP, aromatics and benzene for reformulated gasoline (RFG), compliance is determined based on the complex model estimates of VOC, toxic and NOx emissions relative to the emissions of the 1990 baseline gasoline.
8. Presented here are national average in 2005 based on conventional gasoline survey data. EPA sets limits on benzene and sulfur content as well as summer RVP, but not for other parameters. Individual producer or importer demonstrates compliance with the conventional gasoline standard by showing that emissions of VOC, CO, NO_x and toxic air pollutants from conventional gasoline produced or imported do not increase over levels from the gasoline it produces or imports in 1990. If a producer or importer is unable to develop adequate 1990 data, it must use a "statutory baseline", which is the average quality of all 1990 U.S. gasoline.
9. Refiners and fuel importers could choose to comply with the maximum (flat) limit, or the averaging limit coupled with a cap limit. Refiners and importers could also certify alternative specification by using the predictive model to demonstrate that emissions are equivalent to those of a gasoline meeting the flat limits or the averaging limits plus cap values.
10. Applicable to markets requiring Euro IV, Euro IV heavy duty, US EPA Tier 2 or 2007/2010 Heavy Duty On-Highway or equivalent emission standards.
11. The reformulated gas provision of the Clean Air Act (CAA) limits the aromatic content of RFG to 25% by volume.

12. CAA limits benzene content of RFG gasoline to 1% by volume; the Mobile Source Air Toxics final rule further tightens the benzene limit to 0.62% for all gasoline (reformulated and conventional) on an annual average basis beginning Jan. 1, 2011. While the 0.62% limits could be met through an averaging, banking and trading program, the actual annual average of gasoline produced or imported by any refiner or importer must not exceed 1.3% by volume beginning Jul. 1, 2012.

13. Effective from 2006, the gasoline sulfur limit for all gasoline is 30 ppm for the annual refinery average and a cap of 80 ppm for all production.

14. Applies on December 31, 2011.

15. Clean Air Act specifies a limit of 62.1 kPa (9 psi) for any gasoline sold during the high ozone season (Jun. 1 to Sept. 15). More stringent volatility (summer RVP) requirements are set for RFG, which vary by the region and month, and range from 48.3-62.1 kPa (70-90 psi). EPA provides a 1.0-psi RVP allowance for gasoline containing ethanol at 9 to 10 volume percent.

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17. 47.6 kPa (6.9 psi) applies when a producer is using the evaporative emissions element of CaRFG3 Predictive Model; gasoline may not exceed a cap of 49.6 kPa (7.2 psi); otherwise, the 48.2 kPa (7.00 psi) limit applies.

18. CAA requires that RFG to contain no heavy metal, including lead and manganese.

19. CAA requires that RFG to contain no heavy metal, including lead and manganese.

20. 1.8% winter minimum applies from Nov. 1 to Feb. 29 in the South Coast Area and Imperial County.

21. Applicable to markets requiring Euro IV, Euro V heavy duty, US EPA Tier 2 or 2007/2010 Heavy Duty On-Highway or equivalent emission standards.

22. The California regulations allow flexibility in meeting the limit on aromatics. Producers or importers could either produce a fuel that meets the designated equivalent limits, or certify a fuel formulation by demonstrating that the exhaust emission reduction of a candidate fuel is equivalent to those with the reference fuel; the “low emission” fuels typically have much higher cetane number, lower sulfur, but higher aromatics, higher polycyclic aromatics and higher nitrogen than the reference fuel.

23. The California regulations allow flexibility in meeting the limit on aromatics. Producers or importers could either produce a fuel that meets the designated equivalent limits, or certify a fuel formulation by demonstrating that the exhaust emission reduction of a candidate fuel is equivalent to those with the reference fuel; the “low emission” fuels typically have much higher cetane number, lower sulfur, but higher aromatics, higher polycyclic aromatics and higher nitrogen than the reference fuel.

24. US EPA requires either a minimum cetane index of 40 or a maximum aromatic content of 35%. Premium diesel fuel defined by National Institute of Standards and Technology (NIST) requires minimum cetane number of 47.0. It is up to individual states to adopt the NIST premium diesel requirements.

25. Can be relaxed to 800 kg/m^3 when ambient temperatures are below -30°C. For environmental purposed,

a minimum of 815 kg/m^3 can be adopted.

26. Can be relaxed to 1.5 mm^2/s when ambient temperatures are below -30°C, and to 1.3 mm^2/s when ambient temperatures are -40°C.
27. http://www.osha-slc.gov/dts/osta/otm/otm_iv/otm_iv_2.html
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57. The study found that the effects tended to be larger over higher speed driving than in low speed driving.

58. US EPA models predict that over 12% of the SO_2 emitted in urban areas is converted in the atmosphere to sulfate PM.

59. Similar to the secondary transformation of NO_x to nitrate.

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61. Workstream 1: Evaluation of alternative fuels and technologies for buses in Mumbai, Final report, TERI, 2004, New Delhi: The Energy and Resources Institute. 82 pp. [TERI Project Report No. 2001UT41].

62. SCR systems are completely ineffective if the urea reagent is not added and thus requires great attention to in use enforcement and monitoring when this technology is used. European regulators are taking steps to require fail safe systems that will significantly degrade vehicle performance if the urea tank is not filled.

63. China VI is assumed to be equivalent to Euro 6/VI.

64. It was assumed that all vehicles had a fixed lifetime of 10 years, likely a conservative assumption.