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A Review of Air Pollution Control in Beijing: 1998-2013

UNEP

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May 2016

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Acronyms and Abbreviations

APEC	Asia-Pacific Economic Summit
AQI	Ambient Air Quality Index
ASM	acceleration simulation mode
BCM	billion cubic metres
BRT	Bus Rapid Transit
CNG	compressed natural gas
CO	carbon monoxide
DPF	diesel particle filter
EMBEV 2.0	Emission Factor Model for the Beijing Vehicle Fleet Version 2.0
EPB	Environmental Protection Bureau
ESP	electrostatic precipitator
FGD	flue gas desulphurization
GDP	gross domestic product
HDDV	heavy-duty diesel vehicle
I/M	inspection and maintenance
LNG	liquefied natural gas
MEIC	Multi-resolution Emission Inventory for China

Acronyms and Abbreviations

NAAQS	National Ambient Air Quality Standard
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
O_3	ozone
PEMS	portable emissions measurement system
$PM_{2.5}$	particle matter with aerodynamic diameter of 2.5 µm or less
PM_{10}	particle matter with aerodynamic diameter of 10 µm or less
QA/QC	quality assurance and quality control
SCR	selective catalytic reduction
SNCR	selective non-catalyst reduction
SO_2	sulfur dioxide
tce	tonnes of coal equivalent
THC	total hydrocarbons
TSP	total suspended particulate matter
UNEP	United Nations Environment Programme
VOC	volatile organic compounds
WHO	World Health Organization

Foreword

Evidence for Hope

Many of the world's thriving cities are struggling with serious air pollution, which damages the environment, dampens productivity and has adverse impacts on human health. The scale and complexity of the challenge can be daunting, but this new study reveals sound evidence for hope.

As Beijing is surrounded by mountains on three sides, its topography effectively traps air pollution over the city. At the turn of the millennium, the situation was exacerbated by some troubling parallel trends: a boom in construction; expanding industrial zones; a rising number of vehicles on the road; and a growing population that was using more coal.

Building on efforts dating back to the 1970s, Beijing decided to take aggressive action. In 1998, the government launched a series of measures to offset pollution and improve air quality. The city banned leaded gasoline, introduced catalytic converters in cars, promoted clean energy, introduced electric vehicles, controlled vehicle emissions and upgraded its industrial structure. In addition, an enhanced air quality monitoring network greatly improved data collection, while forecasting tools provided early warnings that could raise public awareness and encourage people to adjust their behaviour.

In the 15 years from 1998 to 2013, the gross domestic product (GDP) of the People's Republic of China increased more than sevenfold. At the same time, in Beijing, resident population grew by 70 per cent, the number of registered vehicles increased by 300 per cent and energy consumption rose by 77 per cent. Remarkably, concentrations of key pollutants, such as sulfur dioxide, nitrogen dioxide and inhalable particulate matter, decreased by 78 per cent, 24 per cent and 43 per cent, respectively. Notwithstanding significant challenges, the city improved air quality even as it maintained its fast-paced growth.

Prior to the 2008 Olympic Games, the United Nations Environment Programme (UNEP) worked with the Beijing Municipal Government to host a sustainable and environmentally friendly event. The following year, UNEP published the Independent Environmental Assessment: Beijing 2008 Olympic Games. It highlighted the city's success in hosting the "Green Olympics" and ensuring improved air quality during the games.

This is not to say that Beijing is out of the woods; additional work is needed to meet standards for particulate matter and, ultimately, to bring health and other benefits. The city is implementing the Clean Air Action Plan 2013-2017, which aims to cut fine particulate matter concentrations by 25 per cent by 2017.

As the capital city of the world's most populous country, Beijing's experience in controlling air pollution against a backdrop of rapid expansion is a story that should be shared with other emerging economies and burgeoning cities. This report focuses on key aspects of Beijing's air pollution strategy: energy structure optimization; coal-fired emission control; vehicle emission control; and enhanced air quality monitoring.

I hope the information in the report will enable scientists and decision makers in both public and private sectors to learn from Beijing's experiences as they address air pollution locally, regionally and globally.

Achim Steiner
UN Under-Secretary-General,
UNEP Executive Director

Foreword

Beijing is a famous ancient capital, with more than 3,000 years of history and more than 800 years as a capital city of different dynasties. Harmony between people and nature has been a highly respected principle in this civilization.

As the capital city of the People's Republic of China, Beijing has achieved great success in performing key functions, including economic growth, improvement of people's lives and city development, during the past 30 years. However, in the process to achieve this, great pressure has placed on the environment and the ecosystem. Air pollution has become the focal point of concern by both the general public and government. It is seen as the key challenge in building a beautiful Beijing.

When the environmental challenge was recognized, Beijing seized the opportunity to prepare and host the 2008 Summer Olympics; it launched the "Green Olympics" concept and the "Green Beijing" campaign afterwards to implement a sustainable development strategy. Programmes for clean energy, green production and low-emission transportation have been developed. An innovative urban traffic network, a low-carbon economy and the implementation of effective air pollution control measures are moving Beijing towards its goal to be a beautiful city. Compared with 1998, the annual average concentration of SO_2, NO_2 and PM_{10} in the ambient air in 2013 decreased by 78 per cent, 24 per cent and 43 per cent, respectively. The deterioration of air quality has ceased and an improvement is being realized, which is helping the city move beyond the first steps towards coordinated development of a strong economy with a protected environment.

The United Nations Environment Programme (UNEP) has consistently extended great support to the environmental protection programmes of Beijing, and has witnessed the city's long-lasting determined efforts to control air pollution.. UNEP has organized an international team of experts to conduct an overall assessment of the effectiveness of the air pollution control programmes. Coal-burning pollution control and energy structure optimization, vehicle emission control, and capacity-building related to air quality monitoring were selected for a quantified assessment. The assessment has generated firm conclusions on the selected areas, while comments and recommendations for the next steps were offered.

Please allow me to express our great appreciation on behalf of the Beijing Municipal Environmental Protection Bureau to UNEP for this publication. We are honoured to share our city's lessons and experience through the UNEP platform with cities still struggling to achieve air pollution control. I hope we can learn from each other and proceed towards building beautiful and livable cities and a better planet for all.

Even though the air pollution control programmes in Beijing have made substantial progress, the environmental quality and ecosystem is far from satisfactory when considering that Beijing functions as the "Political Center, Cultural Center, International Communication Center, and Technical Renovation Center" of China. The citizens of Beijing expect a better environment. The Government of China has published an outline for coordinated development in the Jing-Jin-Ji region (covering Beijing, Tianjin and Hebei), in which environmental protection is considered a leading area to be addressed. We will continue to explore mechanisms and approaches that could work effectively in this region for improving the environment based on the practices we have undertaken over last few years pertaining to joint air pollution control in the Jing-Jin-Ji region and the surrounding area taking advantage of international experience. We welcome the opportunity to interact with the international community through the UNEP platform and hope that our future practices will promote sustainable development in metropolitan and surrounding regions on a larger scale.

CHEN Tian, Director General,
Beijing Municipal Environmental Protection Bureau

Executive Summary

Air Pollution Control in Beijing

Rapid economic and urban growth in Beijing has resulted in the deterioration of the city's air quality.

In 1998, Beijing was highly dependent on coal for its energy needs, with the annual coal consumption reaching as high as 28 million tonnes. This coupled with the more than one million vehicles in the city led to a change from coal-dominated to a mix of coal and vehicle-based air pollution. During that year, the air in Beijing had annual concentrations of carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) of 3.3 mg/m^3, 120 µg/m^3 and 74 µg/m^3, respectively. The average total suspended particulate matter (TSP) concentration was as high as 431 and 348 µg/m^3 during the heating and non-heating seasons, respectively.

Since 1998, Beijing has launched comprehensive air pollution control programmes in phases. A review of control programmes commissioned by the United Nations Environment Programme (UNEP) that focused on coal-fired and vehicle emissions has found that those measures are showing positive trends towards improving the air quality. From 1998 to 2013, the population of Beijing grew by 70 per cent, the number of motorized vehicles increased by 303 per cent and energy consumption rose by 77 per cent. CO and SO_2 levels are now below limits set by the National Ambient Air Quality Standard (NAAQS) of China of 4 mg/m^3 and 60 µg/m^3, respectively. Concentrations of NO_2 and PM_{10} are also closer to meeting NAAQS at 40 µg/m^3 for NO_2 and 70 µg/m^3 for PM_{10}. Additional work, however, is needed to meet standards set by NAAQS and the World Health Organization (WHO) guideline for PM_{10} and $PM_{2.5}$ and ultimately bring health and other benefits.

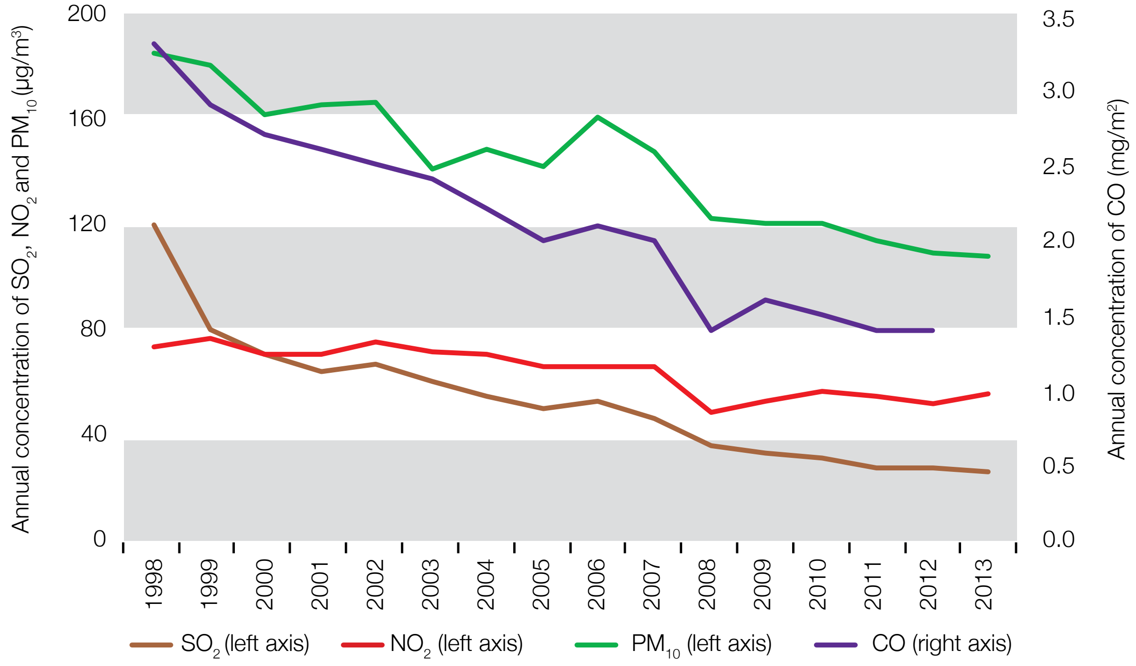


Figure ES1. Annual concentration of air pollutants in Beijing, 1998 – 2013

Source: Beijing Municipal Environmental Protection Bureau, 1998-2014

Reduction in emissions from coal-fired power plants, 1998-2013

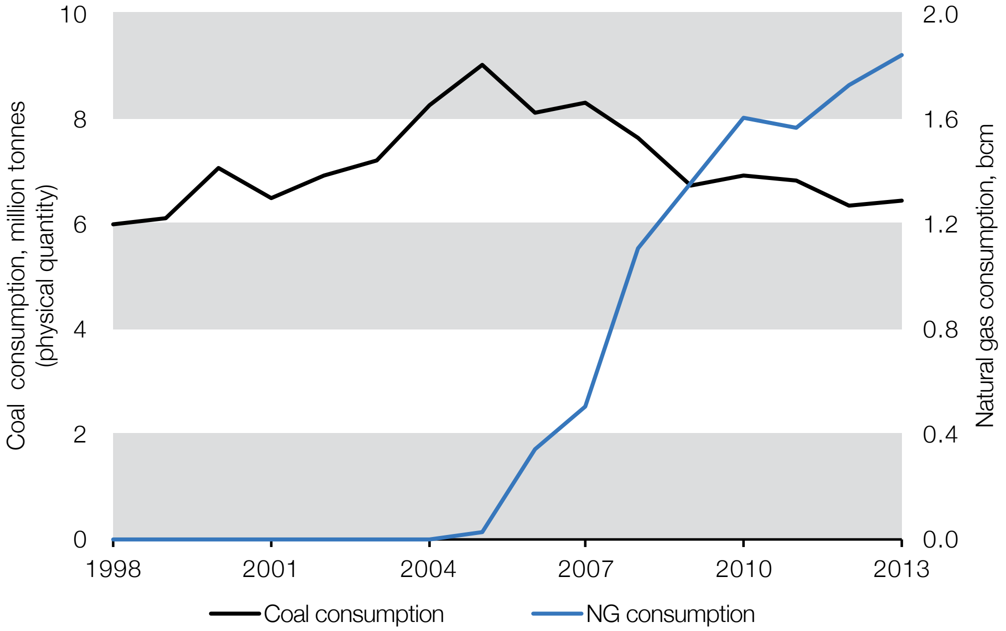


Figure ES2. Coal and natural gas consumption by the power sector in Beijing. 1998- 2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

Annual coal consumption by the power sector in Beijing fell from a peak of 9 million tonnes in 2005 to 6.44 million tonnes in 2013, while natural gas consumption rose from 0 to 1.85 billion cubic metres (bcm) between 2004 and 2013. Combined with end-of-pipe control measures, this helped reduce $PM_{2.5}$, PM_{10}, SO_2 and nitrogen oxides (NO_X) emissions from the city's power plants by 14,500 tonnes, 23,700 tonnes, 45,000 tonnes and 30,900 tonnes, respectively, between 1998 and 2013.

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

Reduction in emissions from coal-fired boilers, 1998-2013

A total of 14,300 tonnes of $PM_{2.5}$, 24,000 tonnes of PM_{10}, 136,000 tonnes of SO_2 and 48,700 tonnes of NO_X emissions were reduced from coal-fired boilers in three phases between 1998 and 2013.

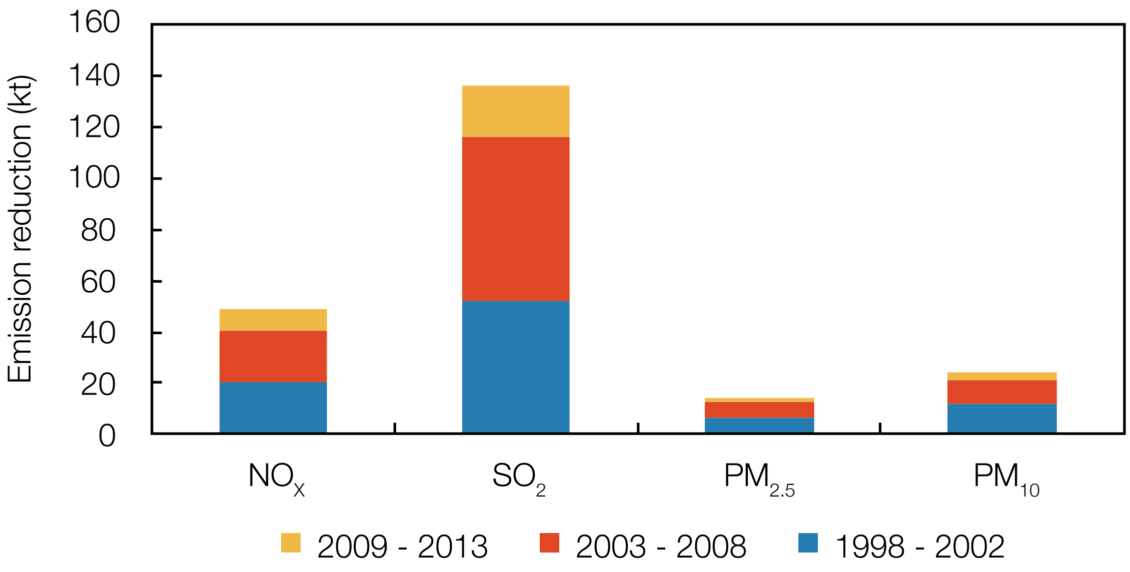


Figure ES3. Avoided emissions from control measures on coal-fired boilers in Beijing

Reduction in coal-fired emissions in residential heating, 2003-2013

Residential heating systems in old one-storey buildings in selected areas of the city were refurbished in two phases to replace coal with electricity. This reduced emissions of 630 tonnes of $PM_{2.5}$, 870 tonnes of PM_{10}, 2,070 tonnes of SO_2 and 790 tonnes of NO_X during the period 2003-2013.

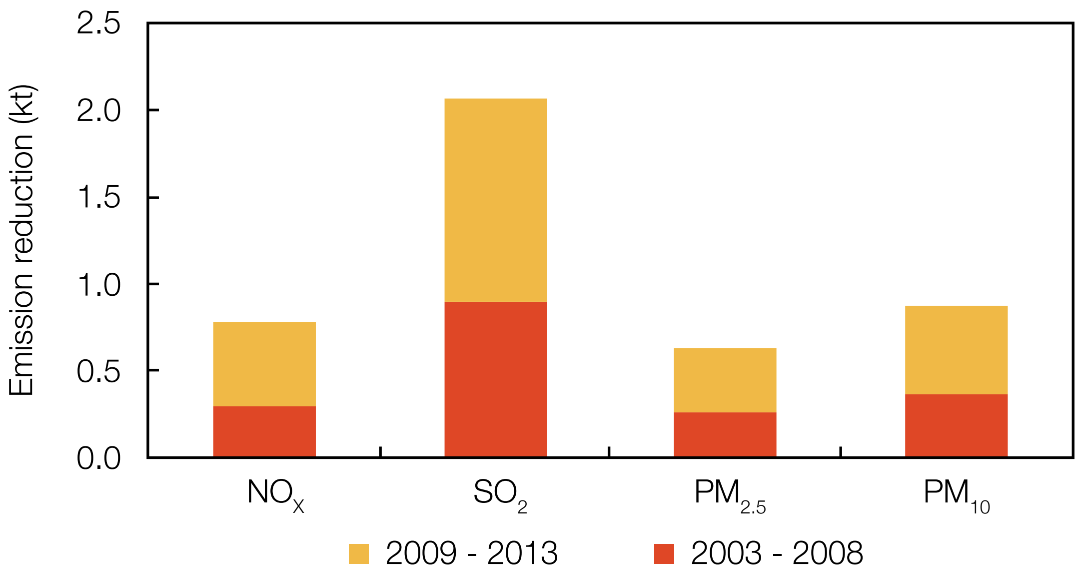


Figure ES4. Avoided emissions from residential heating renovation by replacing coal with electricity in core areas in Beijing with conventional old houses

Reduction in vehicle emissions

Beijing has been implementing integrated emission control measures for vehicles through an integrated package that includes new vehicle control, in-use vehicle control, fuel quality improvement, promotion of clean energy and new energy vehicles, traffic management and economic measures, including, among others, economic incentives to promote the phasing out of older vehicles.

The city is also developing public transport that focuses on rail-based modes and promoting slow-speed traffic modes, such as walking and bicycling Its urban subway has increased from just two lines before 2000 to 18 lines and 527 km of total rail mileage. The share of public transport increased from 26 per cent in 2000 to 46 per cent by the end of 2013.

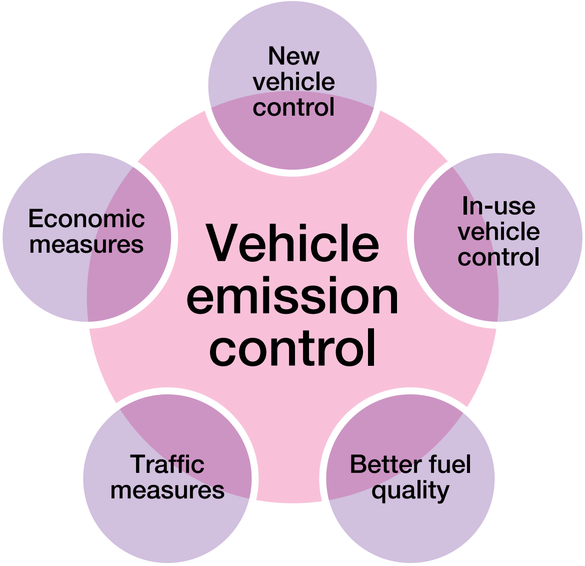


Figure ES5. "Vehicle-Fuel-Road" integrated framework for controlling vehicle emissions

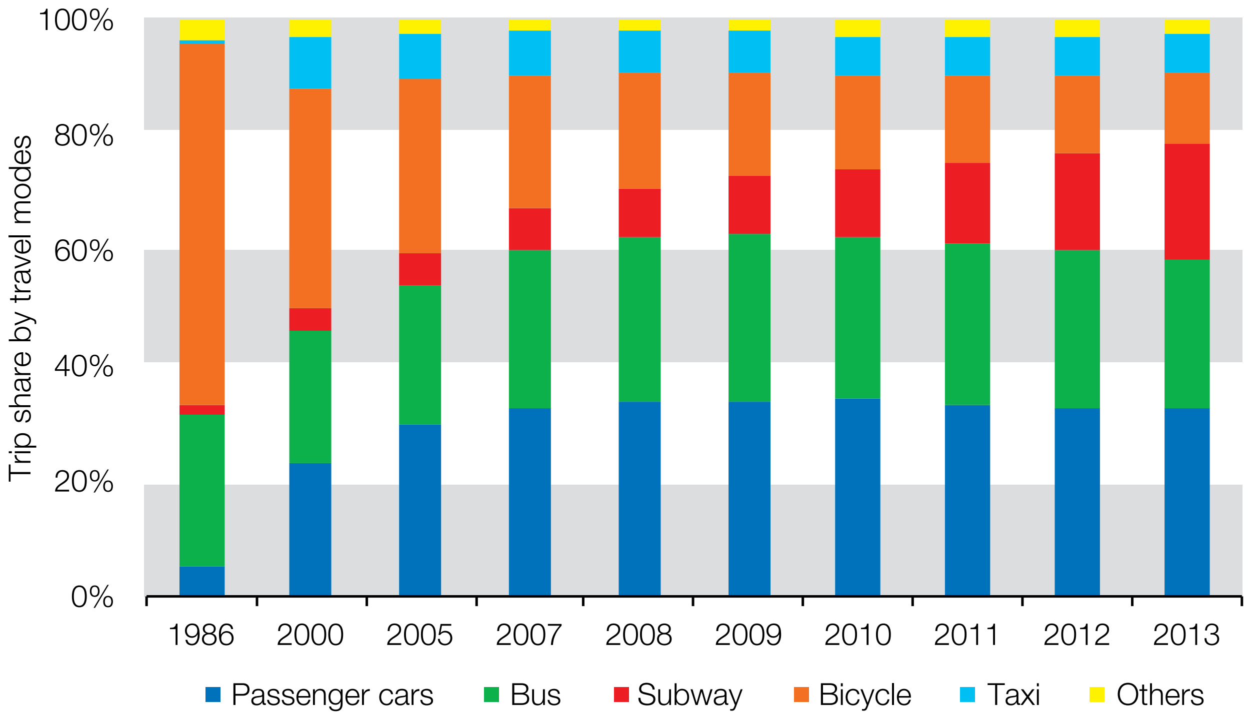


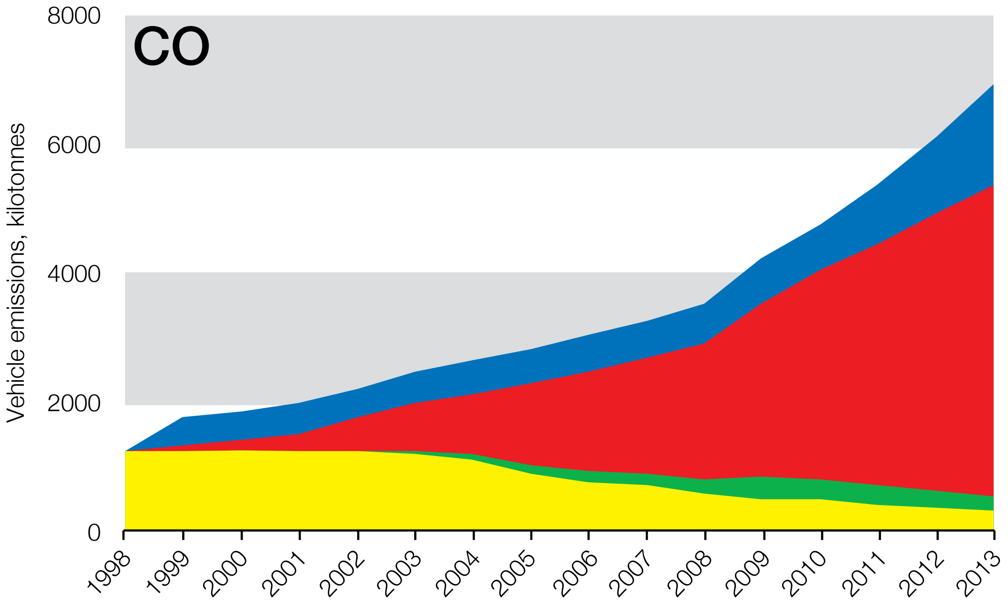
Figure ES6. Modes of transportation in Beijing, 1986- 2013

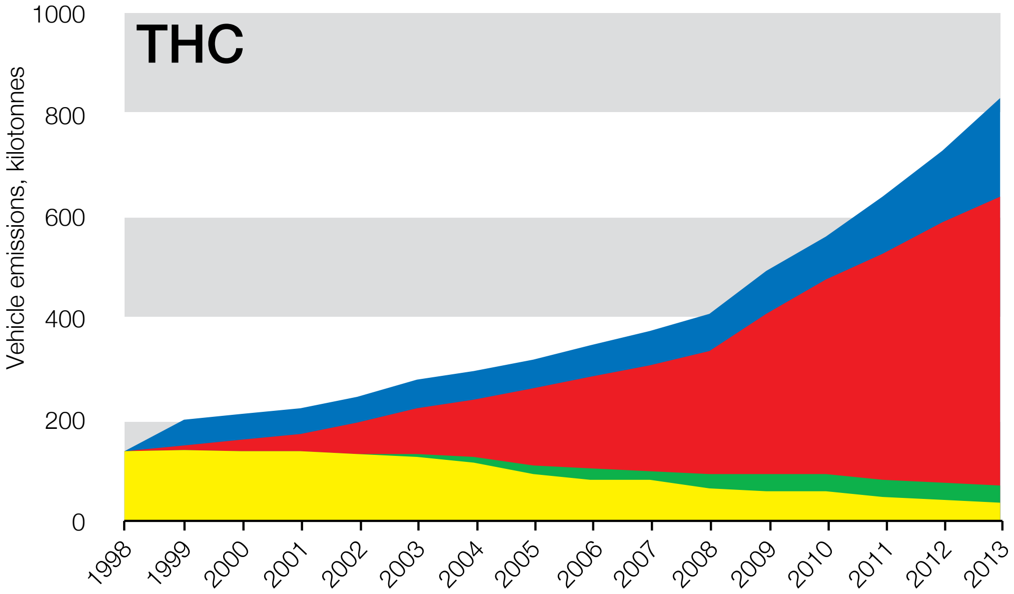
Source: Beijing Traffic Research Center, 2014

Reduction in vehicle emissions, 1998-2013

A series of comprehensive vehicle emission control measures have significantly reduced total vehicle emissions in Beijing. Over the period 1998-2013, those measures have led to cuts in vehicle emissions of CO by 950,000 tonnes, total hydrocarbons (THC) by 103,000 tonnes, NO_X by 43,100 tonnes and $PM_{2.5}$ by 4,900 tonnes compared, with 1998 levels, representing reductions of 76 per cent, 72 per cent, 40 per cent and 70 per cent, respectively.

The reduction in NO_X emissions was lower than other pollutants because of less improved NO_X emission factors for heavy-duty diesel vehicles under urban road driving conditions.





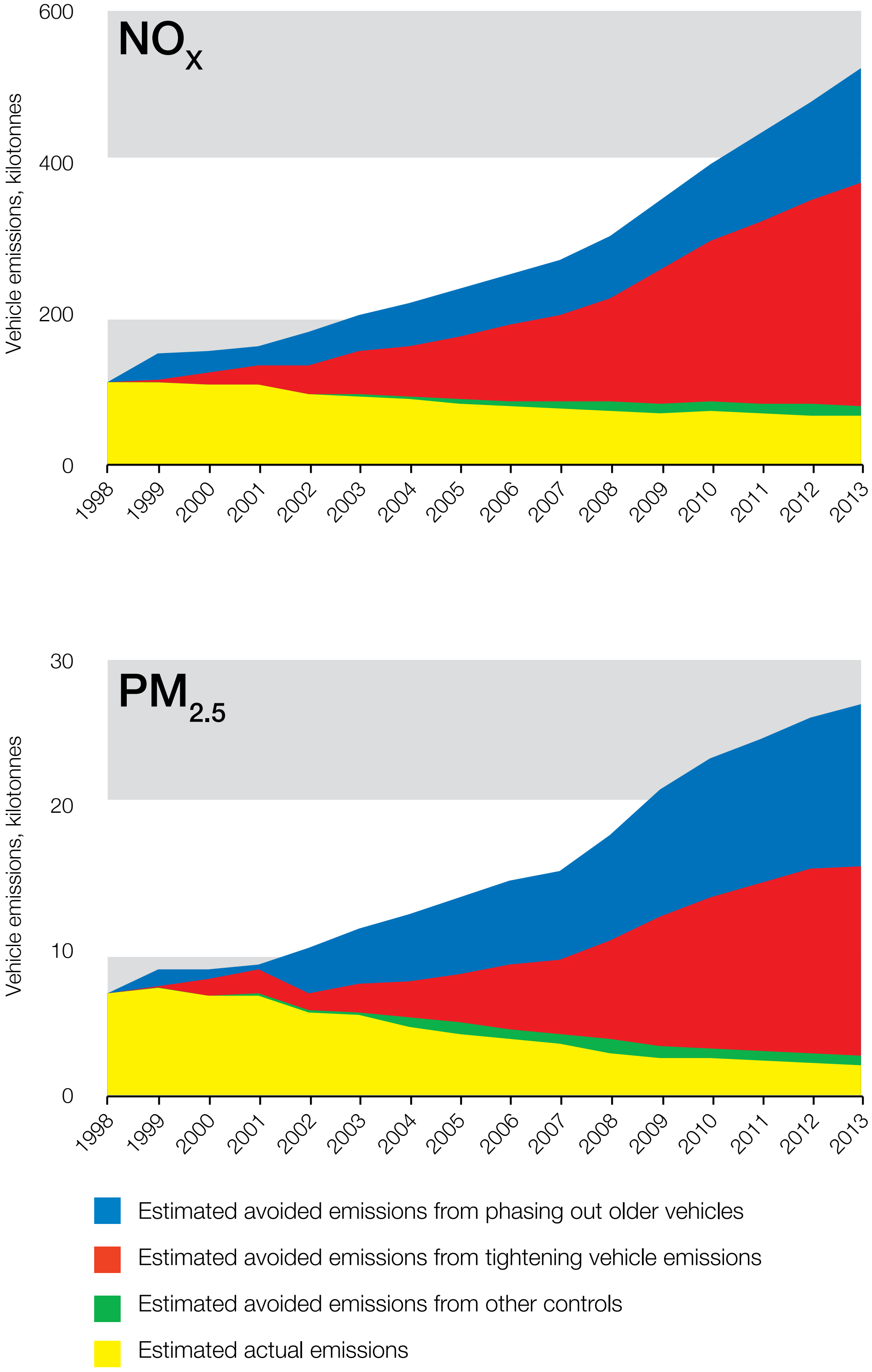


Figure ES7. Estimated vehicle emissions in Beijing

Emission reduction from other measures, 2012

An assessment of vehicle emission reductions in 2012 resulting from a mix of measures — improved fuel quality, an enhanced inspection and maintenance (I/M) programme, and promotion of alternative energy vehicles and traffic control, including driving restrictions, — showed CO, THC, NO_X and $PM_{2.5}$ reductions of 292,000 tonnes, 32,000 tonnes, 14,000 tonnes and 6,700 tonnes, respectively.

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

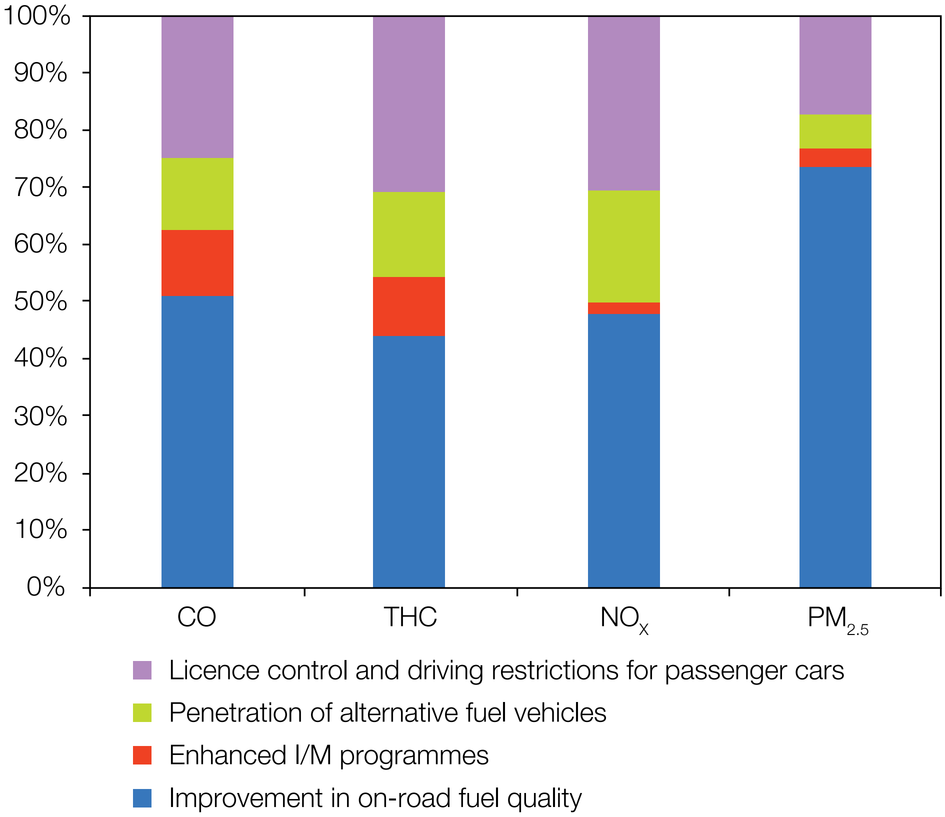


Figure ES8. Avoided emissions from measures additional to vehicle scrappage programme and new vehicle emission standards

PM$_{2.5}$ levels in Beijing

The annual concentration of fine particulate matter (PM$_{2.5}$) in Beijing was 89.5 µg/m^3 in 2013, exceeding the annual limit set by NAAQS by 156 per cent. The PM$_{10}$ level for that year also exceeded the annual limit, by 54 per cent.

Regional transportation emissions accounted for nearly one third of PM$_{2.5}$ concentration in Beijing in 2013. Local emission sources contributed the rest. Depending on the season, regional transport can account for more than half of PM$_{2.5}$ concentration. Local emission sources include on-road vehicles, coal combustion, industrial and construction activities and other sectors.

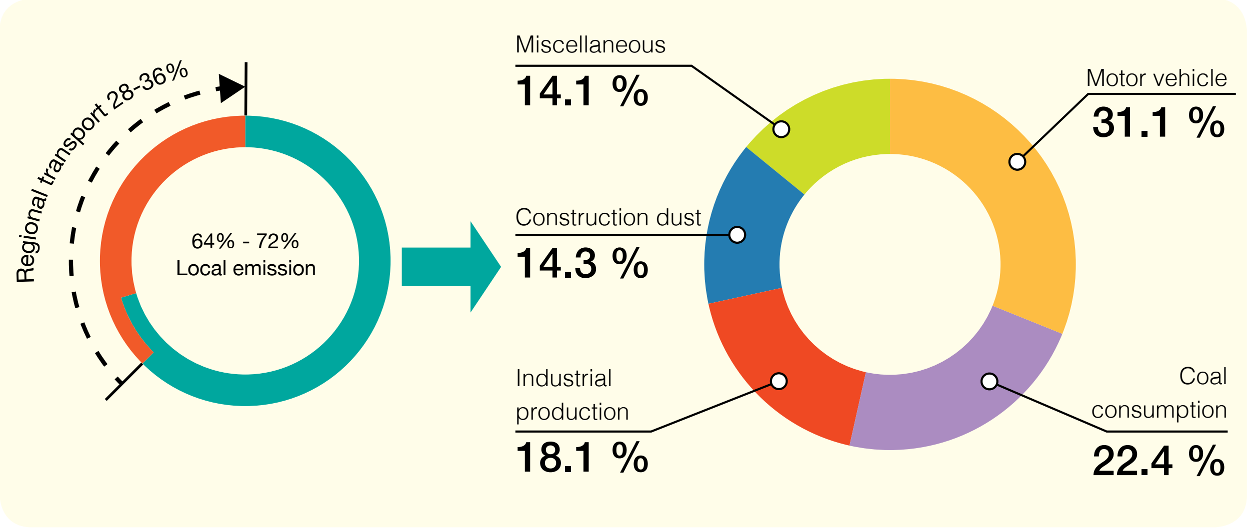


Figure ES9. PM$_{2.5}$ sources in Beijing

Source: Beijing Municipal Environmental Monitoring Center, 2014

Air quality monitoring, 1998-2013

Beijing is developing an air quality monitoring and reporting system, which includes ambient air quality monitoring and forecasting, air pollution source apportionment, and data release. By 2013, 35 ambient air quality monitoring substations had been established across Beijing. Real-time data on concentrations of the six criteria air pollutants are released to the public through multiple channels.

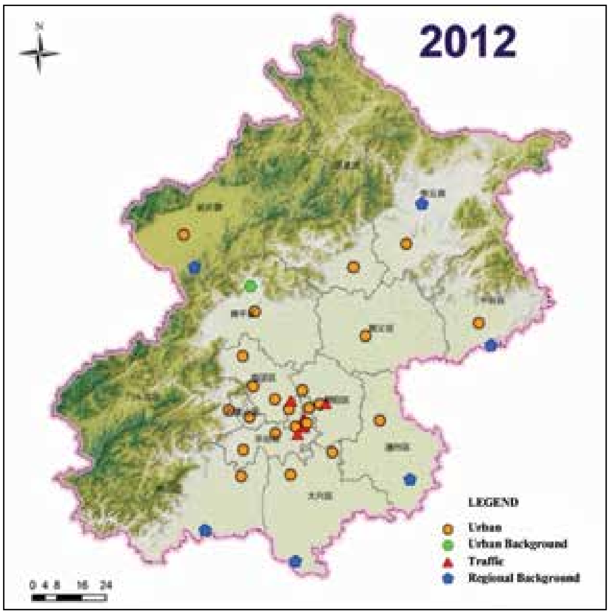


Figure ES10. Location of automatic ambient air quality monitoring system

Source: Beijing Municipal Environmental Monitoring Center, 2012

Chapter 1

Introduction and Background

Beijing, the capital of China, is a rapidly growing metropolitan city with a municipal area of 16,400,000 km^2. By the end of 2014, Beijing had 21.51 million residents, 5.6 million registered vehicles and numerous projects under construction, covering a total area of 565 million m^2. In line with the rapid growth, energy consumption has been increasing to support this prosperous megacity, where per capita gross domestic product (GDP) exceeds US$15,000 (Beijing Municipal Statistics Bureau, 1998-2014). In 2014, total energy consumption in Beijing was 68 million tonnes of coal equivalent (tce). Notably, this figure included a high dependence on coal consumption of 17 million tce. It implies two profound characteristics of this capital city: an obvious pride in the economic development accompanied by pressure to improve its environmental quality.

Figure 1.1 The city of Beijing, capital of China

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

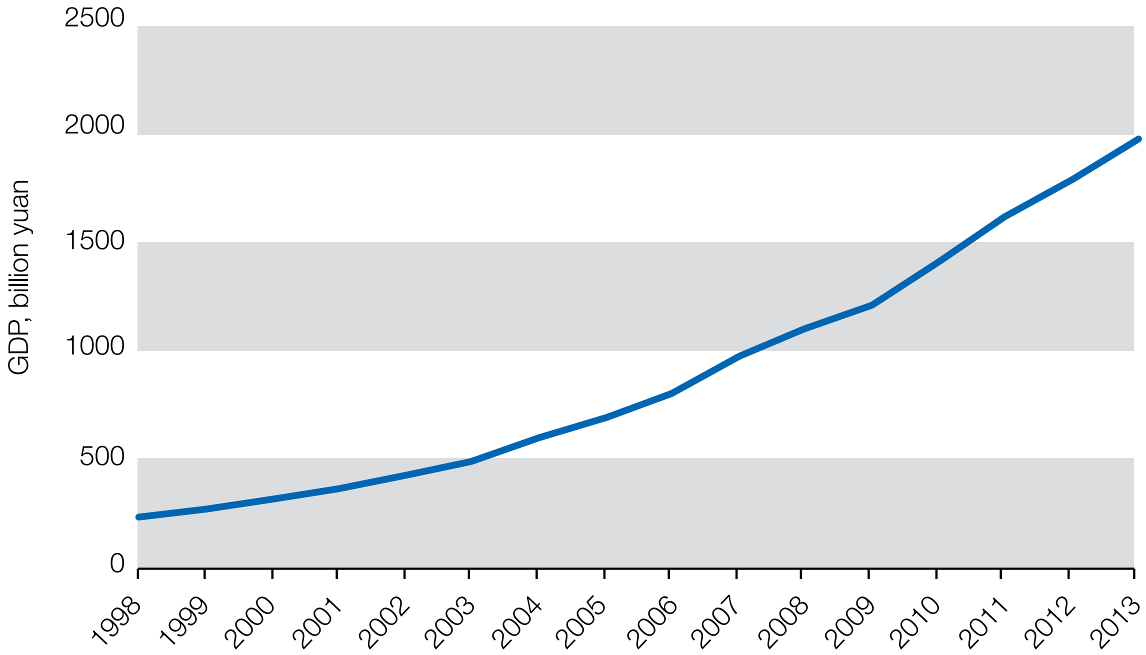


Figure 1.2 Annual gross domestic product in Beijing, 1998-2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

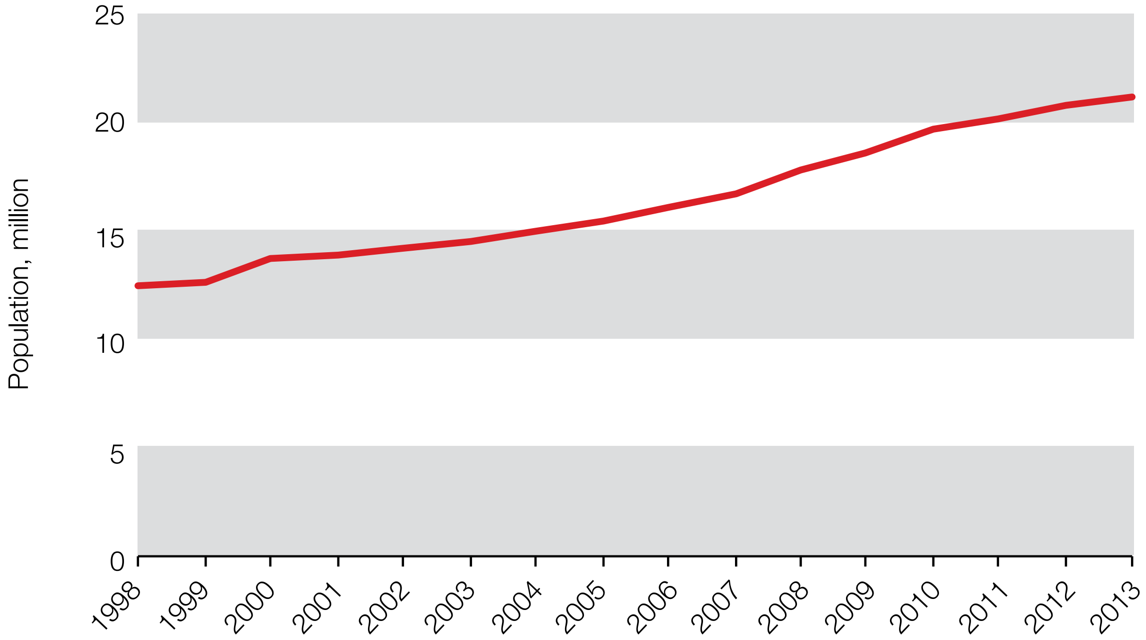


Figure 1.3 Trend of total residential population in Beijing, 1998-2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

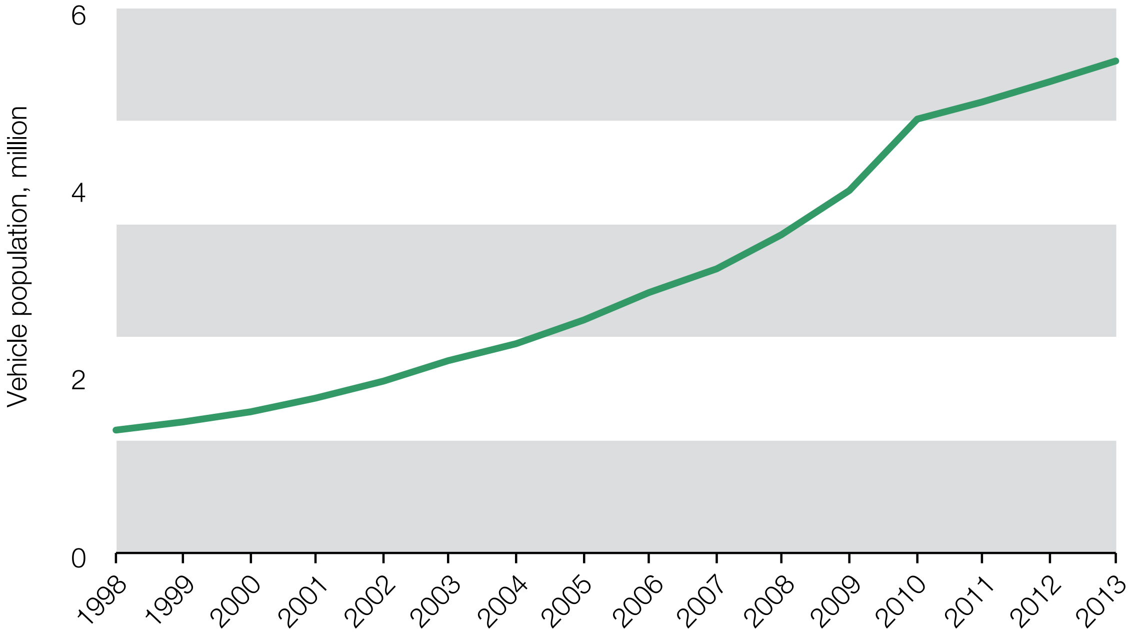


Figure 1.4 Trend of total registered vehicle population in Beijing, 1998-2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

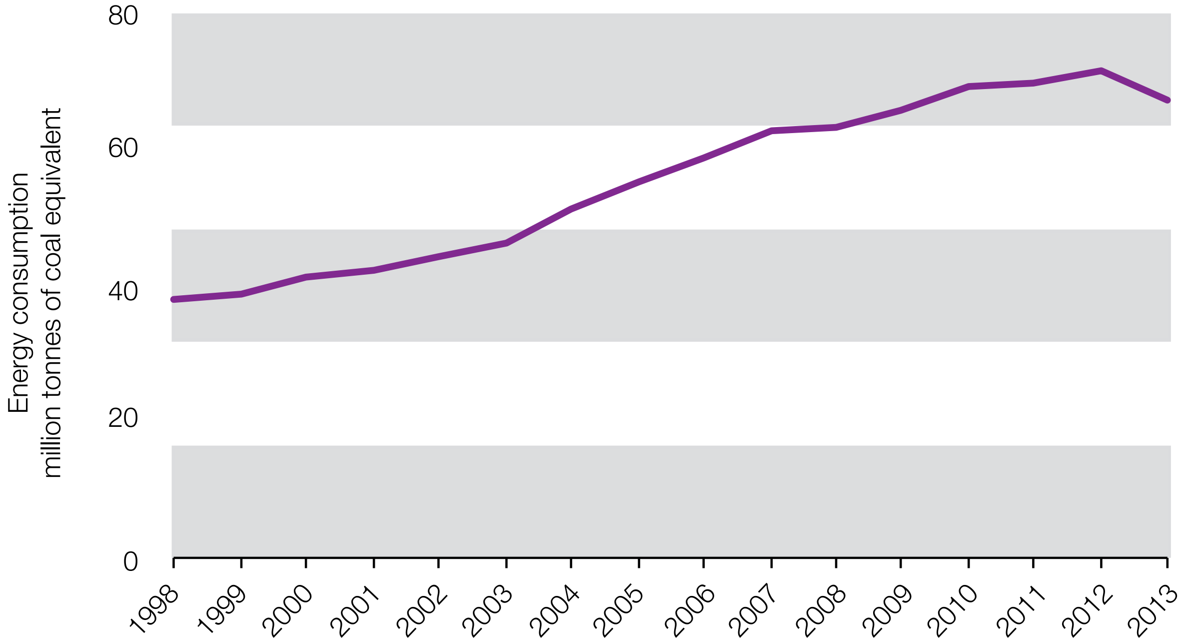


Figure 1.5 Annual total energy consumption in Beijing, 1998-2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

Beijing is a microcosm of many large cities. This megacity's socioeconomic development since the era of reform and opening up began in the late 1970s. It can be summarized by noting the rapid and expanding urbanization and swift industrialization as indicated by the surge in petrochemical, steel and cement plants and soaring vehicle population. Specifically, Beijing suffers from various "urban diseases" with traffic congestion and environmental degradation being two primary symptoms. These symptoms can be attributed to excessive anthropogenic activities, such as coal consumption, use of transport vehicles, operation of industrial plants and urban construction. Air pollution is a major environmental problem in Beijing. Concern over its adverse effects had resulted in the implementation of a series of control measures.

Figure 1.6 Slow-moving traffic on the west side of the Second Ring Road

Photo credit: LIU Jingxing and XIN Yi, Beijing Municipal Research Institute of Environmental Protection

Figure 1.7 A day of bad air quality in Beijing

Photo credit: LIU Jingxing and XIN Yi, Beijing Municipal Research Institute of Environmental Protection

Government efforts to control air pollution can be roughly divided into three periods: in the first period, covering 1970 to 1990, the main focus was on controlling coal-fired air pollution and mitigating emissions of coarse particulate matter; in the second period, which lasted from 1990 to 2002, emissions from industrial plants and on-road vehicles gradually became significant contributors to air pollution; and most recently, since 2000, air pollution in the city has presented complex and regional characteristics, indicated by the significant exceedances of ambient concentrations for fine particulate matter ($PM_{2.5}$) and ozone (O_3).

Since 1998, Beijing has prioritized air pollution control and moved aggressively to control emissions from all sources. The city's efforts in this endeavour over the past 15 years is comprised of several elements — scientific research (emission inventories, monitoring and modelling), coordination (multiple pollutants, all sectors, and join efforts with neighbouring provinces), and the development and implementation of cost-effective control measures. This report, which was produced by a team of experts comprising international and national experts, focuses on three major areas:

(i) Energy structure optimization and coal-related emission control;
(ii) Vehicle emission control;
(iii) Air quality monitoring, early warning, and control and prevention of air pollution episodes.

The aim of the report is to assess the effectiveness of the air pollution control measures and to summarize the city's experience in air pollution control. Chapter 2 reviews the historical trend of ambient air quality in Beijing from 1998 to 2013. Chapter 3 discusses the various air pollution control and prevention measures implemented in Beijing. Chapter 4 assesses the effectiveness of air pollution control measures implemented in Beijing by evaluating the emission reduction benefits. Chapter 5 looks at achieving air quality goal during special events. Chapter 6 summarizes the city's experience in air pollution control and outlines its direction on air pollution control.

Chapter 2

Air Quality in Beijing: Historical Trend and Status Quo

2.1 Historical trend of ambient air quality, 1998-2013

Coal consumption in Beijing in 1998 was 28 million tonnes. It was particularly high in the heating season, eclipsing the amount consumed in the non-heating season by 2.5 times. This high dependence on coal-based energy has resulted in serious air pollution. (Beijing Municipal Statistics Bureau, 1998). Making matters worse, the vehicle population of Beijing started to boom in the 1990s. At that time, a considerable number of the on-road vehicles in the city were equipped with only rudimentary emission controls. Signs of photochemical pollution indicated by excessive O_3 concentration could be discerned under unfavourable meteorological conditions. The surge of vehicles changed the pollution pattern in Beijing from coal-dominated air pollution to a mix of coal and vehicle-based air pollution.

Historical trends of CO, SO_2, NO_2 and PM_{10} are presented in figure 2.1, which illustrates that in 1998, the annual ambient concentrations of CO, SO_2 and NO_2 in Beijing were 3.3 mg/m^3, 120 μg/m^3 and 74 μg/m^3, respectively. Regarding particulate matter concentrations, TSP, which were used as the regulatory metric of ambient air quality monitoring in heating and non-heating seasons were 431 μg/m^3 and 348 μg/m^3, respectively, in 1998 (Beijing Municipal Environmental Protection Bureau, 1998). Beijing started to fully monitor ambient $PM_{2.5}$ concentration starting in January 2013, in line with the revised NAAQS for China.

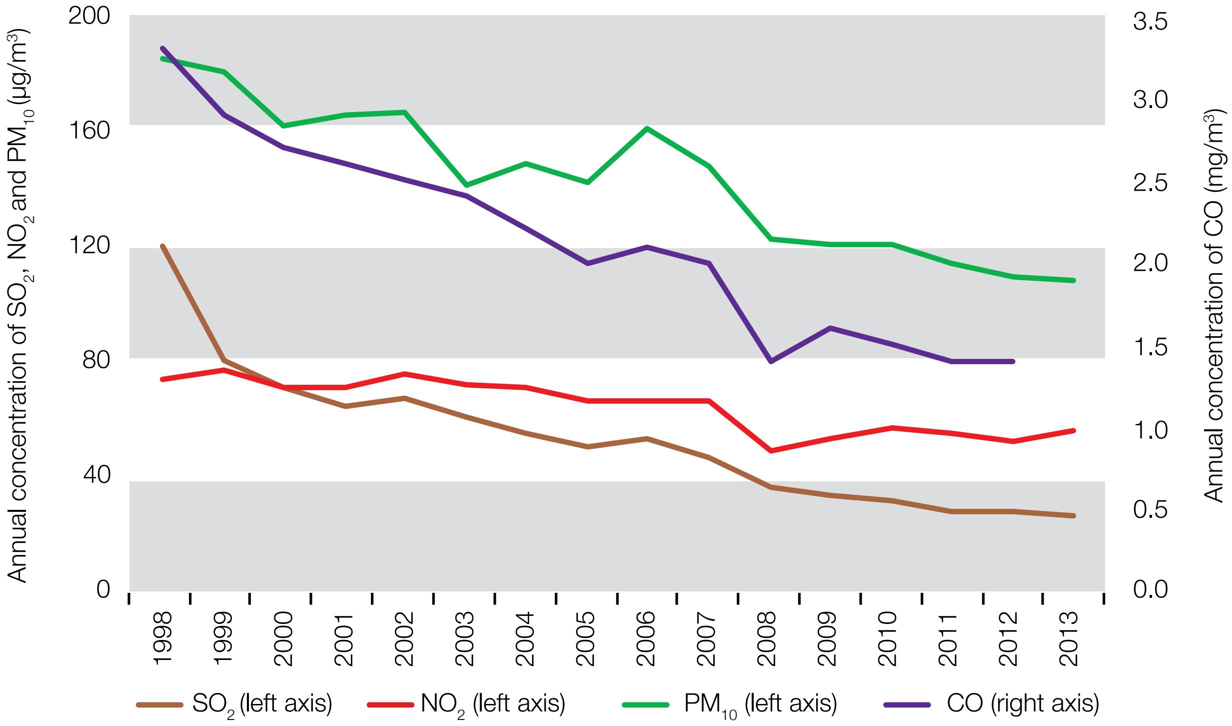


Figure 2.1 Historical trends of annual concentrations for criteria air pollutants in Beijing, 1998-2013

Source: Beijing Municipal Environmental Protection Bureau, 1998-2014

Note: Since 2013, the ninety-fifth percentile maximum value of the 24-h average for CO concentrations has been used by the revised NAAQS (GB3095-2012) as the limit index. Simple annual concentration was used to calculate the concentration of CO prior to 2013.

In 1998, Beijing began to adopt a series of air pollution control measures to combat coal-fired and vehicle-related air pollution problems. This has resulted in descending trends in annual concentrations of major air pollutants in Beijing and provides an indication of the effectiveness of pollution control measures adopted during the past 15 years. In 2013, annual concentrations of SO_2, NO_2 and PM_{10} were 26.5 µg/m^3, 56.0 µg/m^3 and 108 µg/m^3 respectively, which was equivalent to respective reductions of 78 per cent, 24 per cent and 42 per cent, when compared with the levels in 1998. Annual concentrations of CO and SO_2 have been stable, below 1.5 mg/m^3 and 30 µg/m^3 since 2010, meeting the Grade II limits of NAAQS (Beijing Municipal Environmental Protection Bureau, 1998-2014).

2.2 Compliance with national ambient air quality standards set by China

In February 2012, the Ministry of Environmental Protection of China released the NAAQS Amendment (GB3095-2012), which added annual and 24-hr average concentration limits for $PM_{2.5}$, and an 8-h average concentration limit for O_3. The limits of PM_{10} and NO_2 were also tightened (see table 2.1). Starting in 2012, ambient air quality monitoring of $PM_{2.5}$, O_3 and other pollutants have been in required in key regions and cities, including the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta. According to the newly revised NAAQS, annual concentration of $PM_{2.5}$ throughout Beijing was 89.5 µg/m^3 in 2013, exceeding the annual limit of NAAQS, at 35 µg/m^3, by 156 per cent. In addition, the annual concentrations of NO_2 and PM_{10} were 40 per cent and 54 per cent higher, respectively, than the annual limits. The annual ninetieth percentile daily maximum 8-h average concentration of O_3 was 183 µg/m^3, 15 per cent higher than the limit; an O_3 exceedance is more likely to occur in the summer during the afternoon. CO and SO_2 levels were below limits set by the NAAQS of 4 mg/m^3 and 60 µg/m^3, respectively.

Table 2.1 National ambient air quality standards of China (GB 3095-2012)

Pollutant	Unit	Averaging time	Grade I	Grade II	
SO_2	µg/m^3	Annual	20	60	
		24-h average	50	150	
		1-h average	150	500	
NO_2	µg/m^3	Annual	40	40	The 1-h average limits are adjusted from 120 µg/m^3 to 200 µg/m^3.
		24-h average	80	80	
		1-h average	200	200	
CO	mg/m^3	24-h average	4	4	
		1-h average	10	10	
O_3	µg/m^3	Daily max 8-h average	100	160	Newly added, the daily maximum 8-h average limit.
		1-h average	160	200	
PM_{10}	µg/m^3	Annual	40	70	The annual average Grade II limit is tightened from 100 µg/m^3 to 70 µg/m^3
		24-h average	50	150	
$PM_{2.5}$	µg/m^3	Annual	15	35	Newly added
		24-h average	35	75	

Source: Ministry of Environmental Protection of China, and Administration of Quality Supervision and Inspection Quarantine of China, 2012

2.3 $PM_{2.5}$ pollution and control prospects in Beijing

After the release of the new NAAQS in 2012, Beijing conducted a comprehensive source apportionment study on $PM_{2.5}$. This study provided useful information for tackling the $PM_{2.5}$ pollution problem in Beijing. It quantified the proportional contribution of cross-provincial transport and local emission sources, and the proposition of primary pollutants and secondary pollutants. During 2012 and 2013, the Beijing EPB employed advanced source apportionment techniques to refine the source apportionment results (Beijing Municipal Environmental Monitoring Center, 2014). As illustrated in figure 2.2, regional transport accounts for 28 to 36 per cent of $PM_{2.5}$ concentration in Beijing while local emission sources are responsible for the remaining 64 to 72 per cent. It should be noted that regional transport can contribute more than 50 per cent of $PM_{2.5}$ concentration during some heavy haze episodes. Local contributors mainly include on-road vehicles, coal combustion, industrial production, road and construction dust and other sectors, such as catering, vehicle repair, livestock and architecture painting, accounting for 31.1 per cent, 22.4 per cent, 18.1 per cent, 14.3 per cent and 14.1 per cent, respectively. The $PM_{2.5}$ source apportionment results clearly show the complexity of $PM_{2.5}$ pollution and serve as a base for development of control measures required by the Clean Air Action Plan, which are intended to focus on major local sources, such as vehicles, coal combustion, industrial plants and road and construction dust.

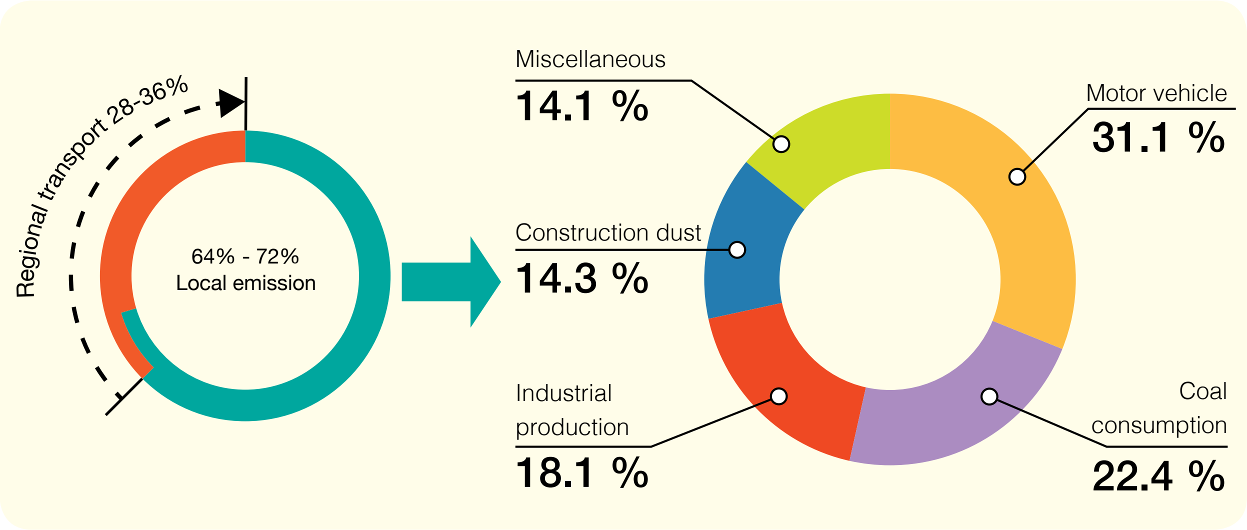


Figure 2.2 The $PM_{2.5}$ source apportionment results in Beijing
Source: Beijing Municipal Environmental Monitoring Center, 2014

Chapter 3

Air Pollution Control Process in Beijing, 1998-2013

Beijing began to undertake air pollution control actions in the 1970s. These actions can be generally classified into three periods based on the pollution sources. In the first period 1970-1990, they were mainly implemented with the objective to mitigate coarse particulate matter emissions and air pollution from coal-fired facilities (boilers, power plants and stoves), which were regarded as the primary stage of air pollution control in Beijing. In the second period, which lasted 10 years, starting in 1990, industrial and vehicle emissions became major sources of air pollution. Since 2000, the city's air pollution pattern is comprised of complex and regional characteristics with $PM_{2.5}$ and O_3 as two significant secondary air pollutants.

The government of Beijing has placed air pollution control as a top priority with regard to environmental protection since 1998, and has implemented a significant number of integrated control measures during the period 1998-2012. The actions cover a variety of fields, including, among them, promoting clean energy, controlling vehicle emissions, upgrading industrial structure, improving air quality monitoring and forecasting, and raising public awareness for air pollution control. In particular, Beijing implemented a Green Olympics action plan during the preparation and hosting stages of the 2008 Beijing Summer Olympics, and followed up with the Green Beijing action plan after the Games. In 2013, the government initiated a comprehensive air pollution control programme, entitled “Beijing Clean Air Action Plan 2013-2017”, for major emission sources with the objective to reduce annual $PM_{2.5}$ concentration in 2017 by approximately 25 per cent compared with the level in 2012. Based on the $PM_{2.5}$ source apportionment results, this report has selected two representative sectors of major air pollution sources, the coal-fired sector and on-road vehicles. The process and effectiveness of air pollution control measures is illustrated and assessed in detail with a primary focus on energy structure optimization, coal-fired emission control and vehicle emission control. In addition, to accurately quantify the contributions by various sectors, monitor major air pollution sources more effectively and reflect on the effectiveness of air control measures, Beijing has enhanced its capacity to monitor air quality, which is also covered in this chapter.

3.1 Energy structure optimization and coal-fired emission control

Coal has long been an important source of energy in Beijing. It is mainly used for heating, power generation, industrial production and residential cooking. Since 1998, Beijing has promoted the structure optimization of energy consumption as part of its effort to improve urban air quality. Primary measures have included implementation of strict emission standards for coal-fired boilers, subsidized replacement and after-treatment, retrofitting of coal-fired boilers, mandatory application of low-sulfur coal and accelerated use of natural gas, imported electricity and other clean energy. Figure 3.1 summarizes a brief history of coal-fired emissions control in Beijing from 1998 to 2013.

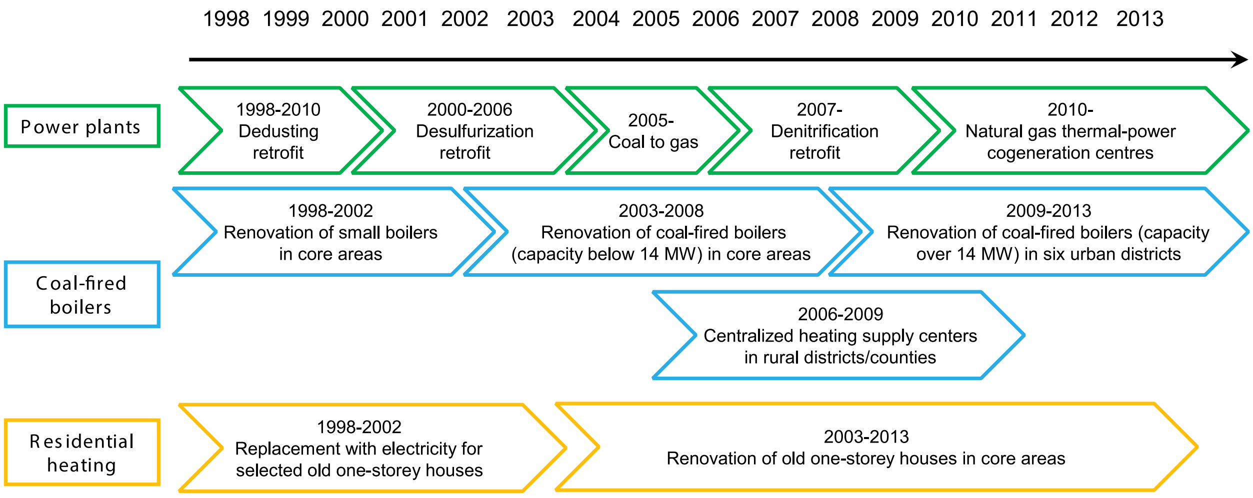


Figure 3.1 A brief history of coal-fired emission control in Beijing, 1998-2013

Through this series of measures, Beijing has greatly improved its energy structure. Over the past 15 years, the city's total coal consumption and proportion of total primary energy consumption has steadily declined. Its effort to optimize energy structure has resulted in a significant reduction in coal consumption. The proportion of coal consumption in total energy consumption decreased from 54 per cent in 1998 to 25 per cent in 2012 (Beijing Municipal Statistics Bureau, 2013). Meanwhile, the proportion of natural gas, imported electricity and other clean sources of energy in total energy consumption increased from 19 per cent to 44 per cent (Beijing Municipal Statistics Bureau, 2013).

(1) Power plants

As a large consumer of coal, the city's power sector began to implement a "coal to gas" strategy in 2005, which has resulted in a gradual increase in the consumption of natural gas in power generation. Over the period 2005-2013, this energy switch has successfully led to negative growth of thermal coal consumption, despite an increase in total electricity generation (figure 3.2). Total annual thermal coal consumption (actual quantity, not unit in tce) by the power sector in Beijing declined from the peak of 9 million tonnes in 2005, to 6.44 million tonnes in 2013, and annual consumption of natural gas for power generation climbed to 1.85 billion cubic meters (bcm) in 2013 (Beijing Municipal Statistics Bureau, 2014). By 2013, natural gas accounted for 35 per cent of total energy consumption by the local thermal power sector in Beijing (Beijing Municipal Statistics Bureau, 2014).

Figure 3.2 A newly built gas-fired power plant in Beijing, 2013

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

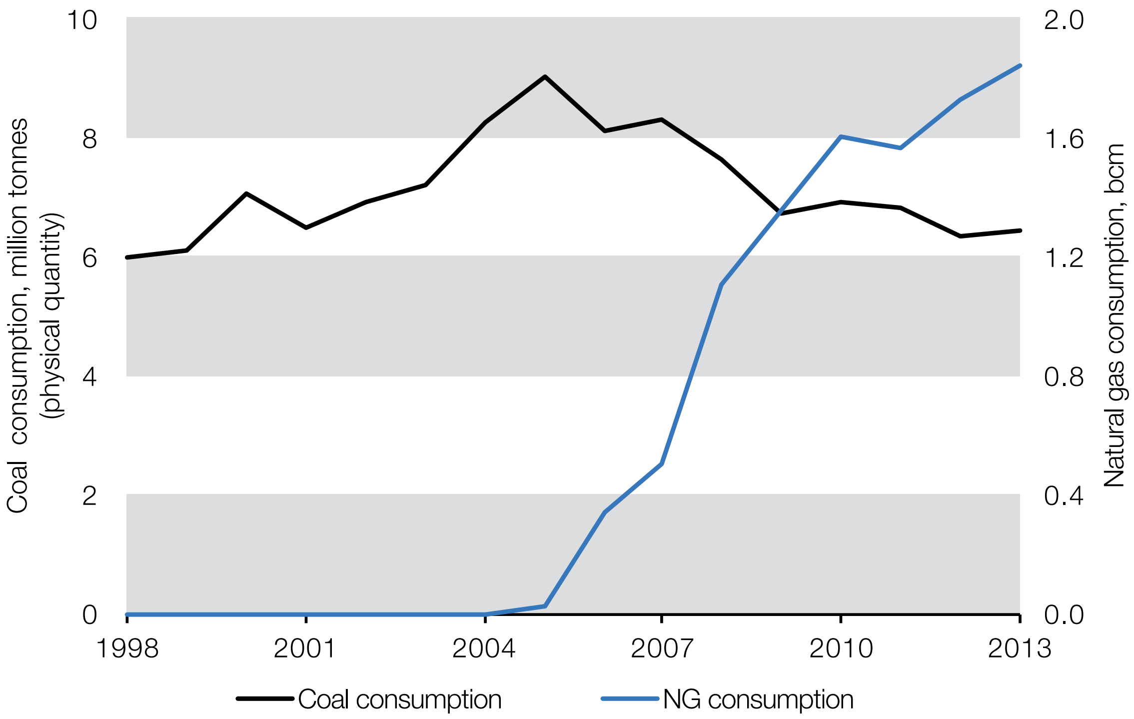


Figure 3.3 Energy consumption by the power sector in Beijing, 1998-2013

Source: Beijing Municipal Statistics Bureau, 1998-2014

In addition to the energy structure optimization and coal-fired emissions control, Beijing deployed strict end-of-pipe control devices. Dust collectors were upgraded during the ninth Five Year Plan period, 1996-2000, and the tenth Five Year Plan period, 2001-2005, flue gas desulfurization (FGD) systems were deployed during the eleventh Five Year Plan period, 2006-2010 and flue gas denitrification systems were installed during the twelfth Five Year Plan period, 2011-2015. The end-of-pipe emission control for coal-fired plants during each stage in Beijing is summarized in table 3.1. Recently, Beijing has implemented one of the most stringent set of emission standards for coal-fired power plants in the world, which includes limiting the. PM in-stack emission limit of new coal-fired units to 10 mg/m^3 (Beijing Municipal Environmental Protection Bureau and Beijing Municipal Administration of Quality and Technology Supervision, 2007).

Table 3.1 End-of-pipe control technologies of major coal-fired plants in Beijing

Power plants	Dedusting	Desulfuration	Denitration
Beijing Gaojing Cogeneration Power Plant	Fabric filter	Wet limestone-gypsum FGD[2]	SCR
Shenhua Guohua Power International Corporation Limited Beijing Cogeneration Branch	ESP	Wet limestone-gypsum FGD	SNCR +SCR
Beijing Huaneng Thermal Power Co., Ltd.	ESP	Wet limestone-gypsum FGD	SCR
Beijing Jingneng Thermal Power Co., Ltd.	ESP, fabric filter, electrostatic-bag precipitator	Desulfurization operation in 1-4 # furnace	SCR

Abbreviations: ESP, electrostatic precipitator; FG, flue gas desulfurization; SCR, selective catalyst reduction; SNCR, selective non-catalyst reduction

(2) Coal-fired boilers

Comprehensive control on coal-fired boilers that are used for industrial and residential purposes is an important priority for air pollution control in Beijing. Since 1998, the city has proactively established coal-free zones in areas where new construction of coal-fired burners have not been approved. According to the Notice on Urgent Measures to Control Air Pollution in Beijing, stoves used by the catering industry in various districts and hot water boilers and stoves of all companies and other coal-fired facilities are required to be replaced gradually by facilities that use cleaner fuels (figure 3.4). In addition, developing new coal-fired facilities are forbidden. Consequently, coal-fired boilers have been primarily rebuilt into natural gas boilers, with a smaller number converted to be run by electricity or oil, or connected to the municipal heating supply network when possible.

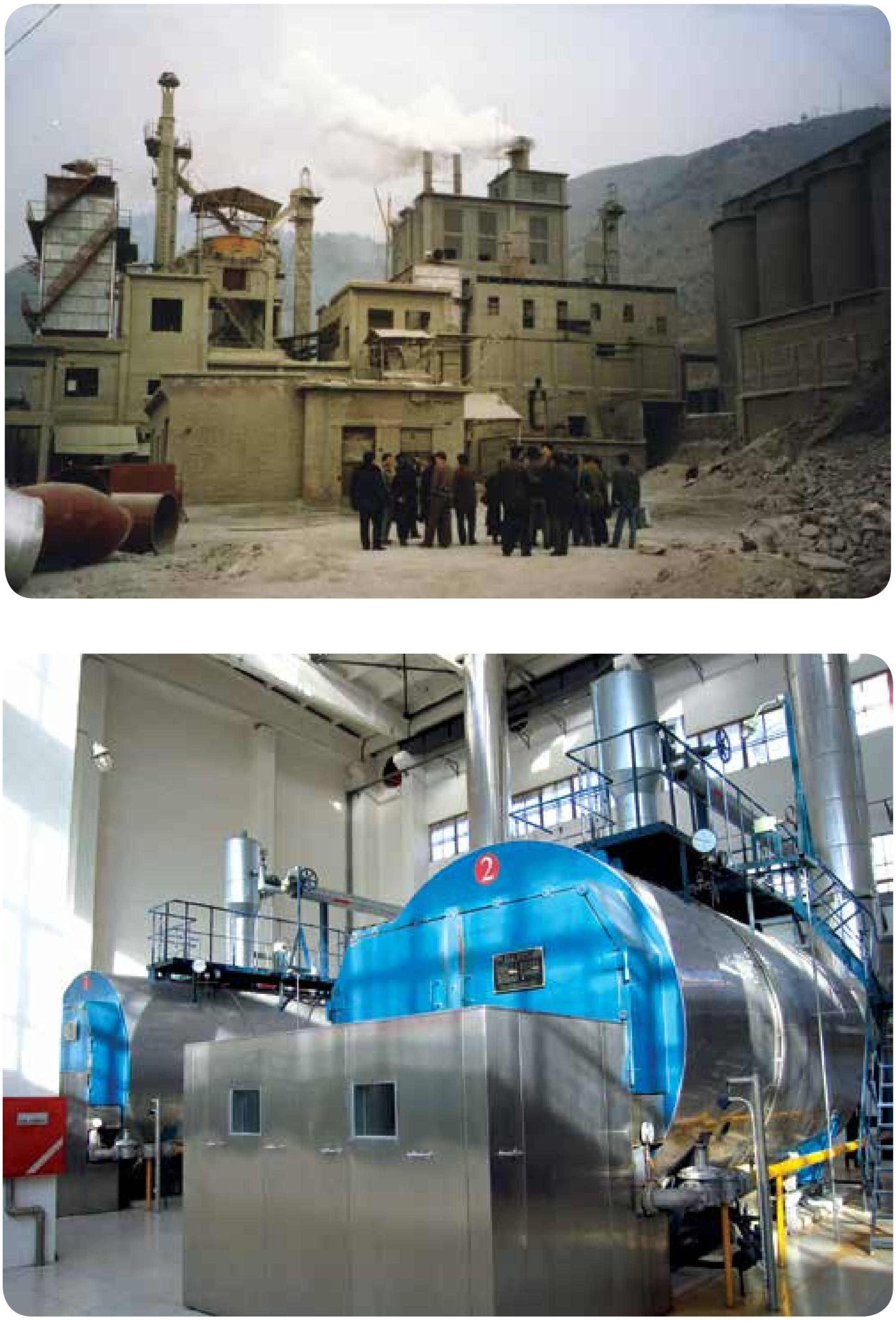


Figure 3.4 Coal-to-clean-energy conversion for boilers

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

The control measures implemented for coal-fired boilers in urban districts can be divided into three phases involving different regions and priorities, as summarized in table 3.2: from 1998 to 2002, the first phase, the major work was to phase out small boilers and stoves with a capacity of less than 0.7 MW in the core areas; from 2003 to 2008, the second phase, the major objective was to phase out coal-fired boilers with a capacity of less than 14 MW in the core areas; and from 2009 to 2013, the third phase, the scrappage expanded to control coal-fired boilers with a capacity of more than 14 MW in six major urban districts.

Table 3.2 Control measures implemented on coal-fired boilers in Beijing, 1998-2013

Period	Area	Focus	Implementation
Phase 1 (1998-2002)	Core areas[a]	Small boilers with capacity less than 0.7 MW	Eliminated 10,633 small boilers, totally phased out capacity of 15,687 MW
Phase 2 (2003-2008)	Core areas	Coal-fired boilers with capacity less than 14 MW	Eliminated 5 704 coal-fired boilers, totally phased out capacity of 15,498 MW
Phase 3 (2009-2013)	Six urban districts[b]	Coal-fired boilers with capacity more than 14 MW	Eliminated 812 coal-fired boilers, totally phased out capacity of 6,436 MW

[a] Core areas refer to Dongcheng and Xicheng districts.

[b] The six urban districts include Chaoyang, Haidian, Fengtai, Shijingshan, Dongcheng and Xicheng.

Source: Compilation from several sources from the Beijing Municipal Environmental Protection Bureau

For suburban districts/counties, such as Shunyi and Pinggu, Beijing implemented centralized heating projects during the period 2006-2009 by shutting down scattered small coal-fired boilers and replacing them with large-capacity boilers of high combustion efficiencies and advanced end-of-pipe control facilities. For example, under the centralized heating project in Tongzhou District in 2007, nine sets of 58 MW coal-fired boilers, five sets of 46 MW coal-fired boilers and a set of 29 MW coal-fired boiler (781 MW in total) were built, and 303 sets of small coal-fired boilers with a total capacity of 1216 MW were shut down. The centralized heating projects in 10 suburban districts and counties of Beijing are listed in table 3.3.

Table 3.3 Centralized heating projects in Beijing suburban districts/counties, 2006-2009

Year	Renovation districts/counties	Number of removed small boilers	Number of newly built large boilers
2006	Shunyi, Huairou, Miyun	110	32
2007	Pinggu, Miyun, Fangshan, Changping, Tongzhou	640	53
2008	Shunyi, Huairou, Yanqing, Daxing	249	20
2009	Shunyi, Fangshan, Mentougou	212	25

Source: Compilation from several sources from the Beijing Municipal Environmental Protection Bureau.

To encourage the renovation of coal-fired boilers, Beijing has implemented a series of incentives to entice the participation of boiler operators. Subsidies are provided based on the total capacity of scrapped coal-fired boilers. For example, for scrapped coal-fired boilers in urban districts, boiler operators are subsidized by 50,000 Chinese Yuan (RMB) per 0.7 MW capacity scrapped; in suburban districts, the subsidies are as high as 55,000 RMB per 0.7 MW and 100,000 RMB per 0.7 MW, respectively, for small and large-size boilers, namely those with a capacity lower than 14 MW and higher than 14 MW.

(3) Renovating heating systems in old house areas

Renovating residential heating systems in the old city centre comprising traditional residential areas, such as the area of quadrangles, was initiated as a trial project (figure 3.5). For example, as public infrastructure in the old city centre, in such districts as Dongcheng and Xicheng, was outdated and the hutongs were narrow, the old houses there could not be integrated into the centralized heating system or the natural gas supply network. After careful evaluation and consideration, converting to electric heating systems was determined to be a reasonable and feasible option that would preserve the valuable tradition and architecture features of the conservation areas. In addition to being charged lower electricity prices during non-peak hours, the residents of those old houses are receiving subsidies from their local governments for their electricity. Therefore, the actual cost of electric heating after the renovation is comparable and even lower than previously used coal-burning heating. Progress in converting the heating systems in the old house areas is shown in table 3.4.

Figure 3.5 Electric heating device for residents in old house areas

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

Table 3.4 Residential heating conversions in the old city centre traditional residential area of Beijing, 1998-2013

Period	Area	Household
Phase 1 (1998-2002)	Pilot projects in selected neighbourhoods	256
Phase 2 (2003-2008)	Selected neighbourhoods	93 500
Phase 3 (2009-2013)	Whole core areas	150 000

Source: Compilation from several sources from the Beijing Municipal Environmental Protection Bureau.

3.2 Integrated control of vehicle emissions

The rapid growth of the vehicle population since 1998 has triggered a serious challenge to the air quality in Beijing. Vehicle emissions have contributed to primary pollutants, such as NO_2, and secondary pollutants, such as O_3 and $PM_{2.5}$. The adverse effects are significantly reflected in the following two aspects. First, the primary pollutants of vehicle emissions accumulate to a high pollution level in traffic-populated urban areas; for example, Tsinghua University revealed that vehicle emissions had become the most important source of CO and NO_2 in urban areas of Beijing in 2000 (Hao et al., 2000). Second, (THC and NO_X from on-road vehicles are important precursors of secondary pollutants, including $PM_{2.5}$ and O_3, through complex atmospheric chemical reactions. The results of $PM_{2.5}$ source apportionment released by the Beijing EPB in 2014 indicated that the contribution of vehicle emissions topped all local emission sectors, accounting for 31.1 per cent of the annual average of all $PM_{2.5}$ concentration contributed by local sources.

Among the sixteen-stage air pollution control measures, vehicle emission control has always been a priority. Beijing has formulated and amended more than 30 local standards pertaining to new vehicle emissions, in-use vehicle emissions and fuel quality. The city has continuously tightened emission standards for new vehicles, enhanced inspection and control of in-use vehicles and improved fuel quality, including promoting clean fuels and new energy vehicles. Since 2008, increased attention has been paid to traffic management and economic tools through a "Vehicle-Fuel-Road" integrated framework to control vehicle emissions (see figure 3.6). In addition, figure 3.7 shows the major measures and the implementation timetable of vehicle emission control in Beijing.

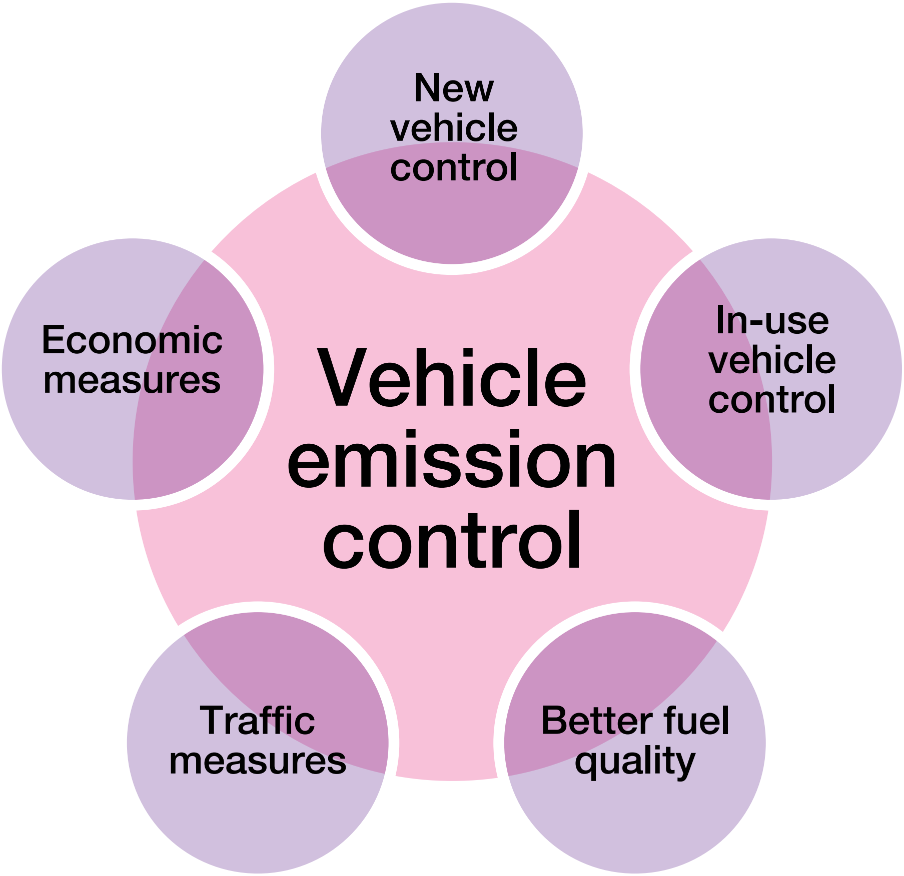
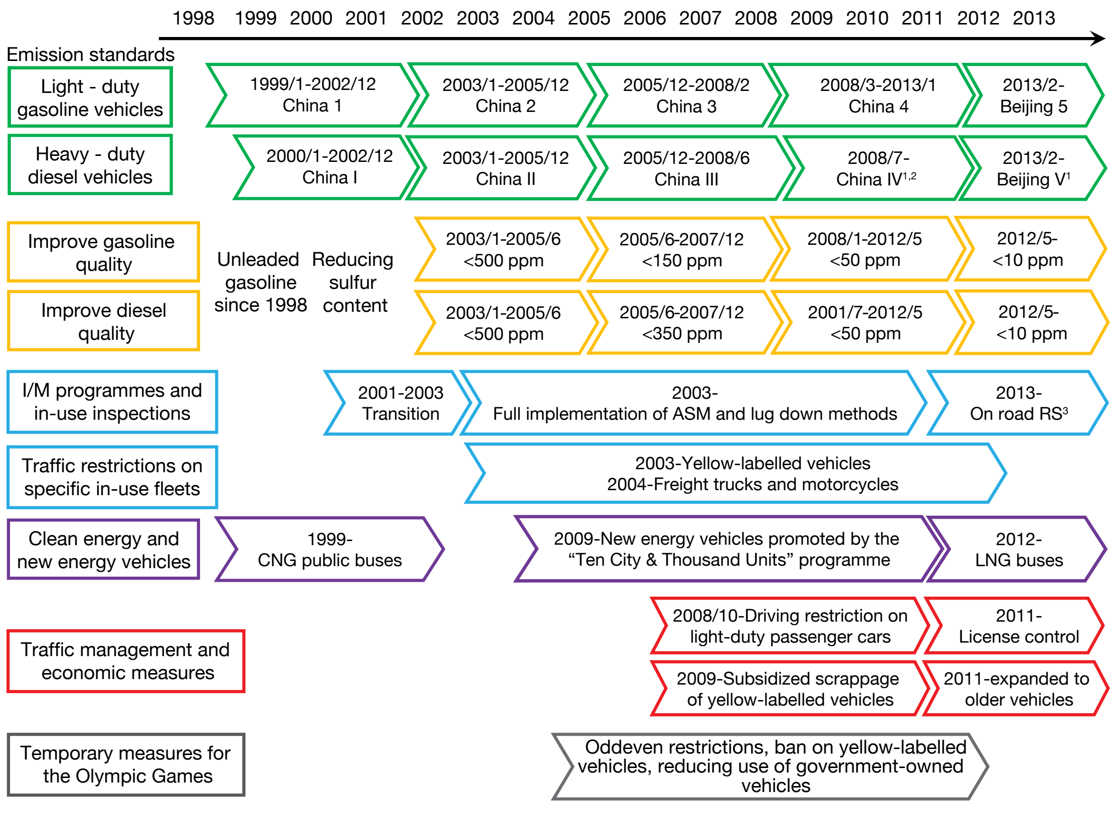


Figure 3.6 "Vehicle-Fuel-Road " integrated framework for controlling vehicle emissions



[1]Only implemented for public fleets; [2]for freight trucks and long-distance coaches, they complied with the China IV emission standard from July 2013 as required by the Ministry of Environmental Protection; [3]remote sensing test

Figure 3.7 Major measures and implementation timetable of vehicle emission control in Beijing

Abbreviations: ASM, acceleration simulation mode; RS, remote sensing; I/M, inspection and maintenance; LNG, liquefied natural gas

(1) Emission control on new vehicles

Implementing vehicle emission standards to strengthen the new vehicle emission control is a core component of the vehicle emission control system. In January 1999, Beijing became first city in China to implement the China 1 emission standards (equivalent to the Euro 1 standard) for light-duty gasoline vehicles. Since then, Beijing has been the leading city in controlling emissions of new vehicles. In fact, it has subsequently implemented emission standards earlier than national requirements for both light-duty gasoline vehicles and heavy-duty diesel vehicles from the China 2/II to the China 4/IV. In February 2013, Beijing became the first Chinese city to implement the Beijing 5/V emission standards, which is almost equivalent to the China 5/V formulated by the Ministry of Environmental Protection, further narrowing the gap in terms of stringency of new vehicle emission control with advanced countries, including European Union member countries, the United States and Japan.

Table 3.5 Implementation date of emission standards for new vehicles in Beijing, 1999-2013

Vehicle category	China 1/I	China 2/II	China 3/III	China 4/IV	Beijing 5/V
Light-duty gasoline vehicle (LDGV)	1999-1-1	2003-1-1	2005-12-30	2008-3-1	2013-2-1
Heavy-duty gasoline vehicle (HDGV)	2002-7-1	2003-9-1	2009-7-1	2013-7-1	
Heavy-duty diesel vehicle (HDDV)	2000-1-1	2003-1-1	2005-12-30	2008-7-1 [a] 2013-7-1 [b]	2013-2-1 [a]
Motorcycle	2001-1-1	2004-1-1	2008-7-1		

[a] Only implemented in public fleets, such as public buses, sanitation and postal vehicles, not including commercial freight trucks and long-distance coaches;

[b] For freight trucks and long-distance coaches, they complied with the China IV emission standard as required by the Ministry of Environmental Protection

Source: Zhang, 2014.

In addition to tightening local emission standards for new vehicles up to the China 5/V standards, Beijing has also conducted strict type-approval conformity supervision over the vehicle market. The vehicle specifications are carefully checked to assure that key emission control technologies, such as engine technologies and after-treatment devices, are installed in compliance with those set in the type-approval test. As a result, it has become more difficult for counterfeit vehicles to penetrate the city's fleet, which, in turn, helps ensure the potential benefits from the increasingly tightened emission standards. Furthermore, in the light of local conditions, Beijing has not allowed the registration of light-duty diesel vehicles since 2003 (Zhang et al., 2014a). Consequently, relevant air pollution problems, such as high NO_2 concentration, associated in part with diesel cars, are avoided in Beijing. Over the past 15 years, Beijing has not only strengthened emission standards for new vehicles, but it has also ensured supervised implementation of the strengthened standards.

(2) Emission control of in-use vehicles

Effective inspection and control measures of in-use vehicles can mitigate emissions over the entire vehicle lifespan, and, in particular, identify and manage high-emitters to aid in achieving lower fleet-average emission levels. From 1998 to 2013, Beijing implemented a number of in-use vehicle emission control measures, including: retrofitting of 300,000 older carbureted vehicles by adding after-treatment devices; implementing a pilot retrofit programme to install diesel particle filters (DPF) for in-use diesel vehicles; enhancing vehicle inspection and maintenance (I/M) programmes by improving test methods for annual inspection and initiating an environmental labelling policy for managing high emitters; and imposing driving restrictions on motorcycles, trucks and yellow-labeled vehicles, indicating high-emitters, such as pre-China 1 LDGVs and pre-China III HDDVs, within the urban areas. Additionally, the city introduced remote sensing and other advanced t echniques to detect on-road high-emitters, promoted a driving restriction area policy for those high emitters (similar to low emission zone policies in European countries) and offered economic incentives to promote the turnover of older vehicles.

In 1999, Beijing amended the test methods for two-speed idle and adopted different limits for China 1 gasoline cars. In 2001, the city began to adopt more stringent acceleration simulation mode (ASM) test procedures; the ASM test procedures were further revised in 2003 and their emission limits of air pollutants were tightened in subsequent years based on the stage of new vehicle emission control in Beijing. As for heavy-duty diesel vehicles, Beijing adopted a lug-down test method in 2003 and tightened its smoke emission limits in 2010. By 2014, Beijing had established 43 inspection stations equipped with 200 lanes for the vehicle inspection tests.

In addition to annual inspection for in-use vehicles, an enhanced on-road test is an important technique for monitoring in-use vehicle emissions. Beijing has set up stationary and mobile remote-sensing devices to inspect on-road vehicles, including 86 remote-sensing sites by November 2014. After high-emitters that exceed regulatory limits through remote sensing are identified, the Beijing EPB notifies the vehicle-owner, releases the monitoring results to the public on its website and performs appropriate on-site or off-site enforcement actions.

Beijing established an environmental labelling and management policy when the China 1 emission standards were implemented in 1999. For example, pre-China 1 light-duty gasoline vehicles and pre-China III heavy-duty diesel vehicles are now issued yellow labels. As driving restrictions increase for those targeted yellow-labelled vehicles, the scrappage is accelerated for the high-emitters. Furthermore, Beijing has taken effective actions to control vehicle emissions from public and commercial fleets, such as taxis, public buses, postal and sanitation vehicles, and construction trucks, that, in general, have higher use intensity than private cars. Two of those actions are promoting scrappage of older vehicles and retrofitting other vehicles with emission control devices. For example, Beijing has offered substantial subsidies since 2009 to scrap yellow-labelled vehicles and other older vehicles. Those subsidies are elaborated in the sections on economic incentives.

(3) Improvement in fuel quality

Efforts of to improve fuel quality for on-road vehicles in Beijing began in the 1990s. In June 1997, the eight urban districts of Beijing started to deliver unleaded gasoline to the market. Later, in January 1998, unleaded gasoline became fully available in all the administrative districts, making Beijing the first city in China to successfully have phased out leaded gasoline. Since then, Beijing has gradually reduced the sulfur content of gasoline and diesel fuel in order to ensure the implementation of tightened emission standards for new vehicles and the effectiveness of emission control devices. Beijing is one of very few cities in China where standards of new vehicle emissions and fuel quality have been simultaneously tightened over the past fifteen years, and the sulfur content limits of both gasoline and diesel fuels are completely consistent with those adopted in Europe since the second stage, namely the China 2/II. Beijing implemented local fuel quality standards from the China 3/III to the China 5/V for on-road gasoline and diesel fuels from 2005 to 2012. In particular, for the China 5/V fuel quality standards, the sulfur content of both gasoline and diesel fuels must be lower than 10 ppm in order to comply with the future application of advanced after-treatment devices, such as DPF.

In addition, Beijing has adopted multiple control measures for reducing evaporative emissions of on-road gasoline during the storage and refueling processes. For example, in 2008, the city retrofitted more than 1,000 gasoline stations, 1,000 oil tank trucks and 50 oil storage tanks by adding gasoline vapor recovery systems (figure 3.8).

Figure 3.8 Implementation of the Gasoline Vapor Recovery System in gas stations and oil storage tanks in Beijing

Photo credit: Beijing Municipal Publicity Center for Environmental Protection

(4) Promotion of clean fuels and new energy vehicles

Compressed natural gas (CNG) buses were introduced in Beijing in 1999. By 2009, 29 CNG stations had been built to serve more than 4,000 CNG buses. The city can now boast that it has one of the largest CNG-powered bus transit fleets in the world (Zhang, 2014).

With support from a series of policies set by central and local municipal governments, Beijing has introduced hybrid diesel electricity buses, battery electric buses and liquefied natural gas (LNG) buses for public transportation service. During the period 2013-2017, Beijing has a clear goal to actively promote those clean fuels and add new energy vehicles, such as natural gas vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles, to urban public fleets, such as public buses, taxis, sanitation and postal vehicles (figure 3.9). Construction of important supplementary infrastructure, including natural gas stations and charging facilities, will be accelerated. Also, the current licence control policy for light-duty passenger vehicles has been configured with a special quota for new energy cars by implementing a separate licence-plate lottery system to encourage private purchases of new energy cars.

Figure 3.9 Fuel-cell-driven buses (top) and promotion of public transportation (bottom) in Beijing

Photo credit: Beijing Municipal Research Institute of Environmental Protection

(5) Transportation and traffic management

Over the past 20 years, the population of Beijing as well as the number of vehicles in the city have increased sharply. As a result, the city faces many challenging issues, including, among others, severe traffic congestion, high vehicle population, deteriorating air quality and limited space for expansion of roads. To deal with these issues, Beijing is focusing on optimizing urban planning, developing public transport and slow-speed traffic modes, such as walking and bicycling, implementing effective traffic control measures to optimize travel modes and reducing the contribution to air pollution by transportation.

In terms of public transportation, Beijing is placing high priority on developing and promoting its urban public transport network with the rail-based transportation system. The urban subway in Beijing increased from only two lines prior to 2000 to 18 lines by the end of 2014, and total rail mileage reached 527 km. For the ground transportation system, Beijing opened the south-central Bus Rapid Transit (BRT) in 2004 and set up special lines and added commuter buses. In particular, bus lanes were established on the the Jing-Tong Expressway in 2011. The total travel mode share of public transportation (including rail-based and ground transportation has increased from 26 per cent in 2000 to 46 per cent by the end of 2013 (figure 3.10) (Beijing Transportation Research Center, 2014).

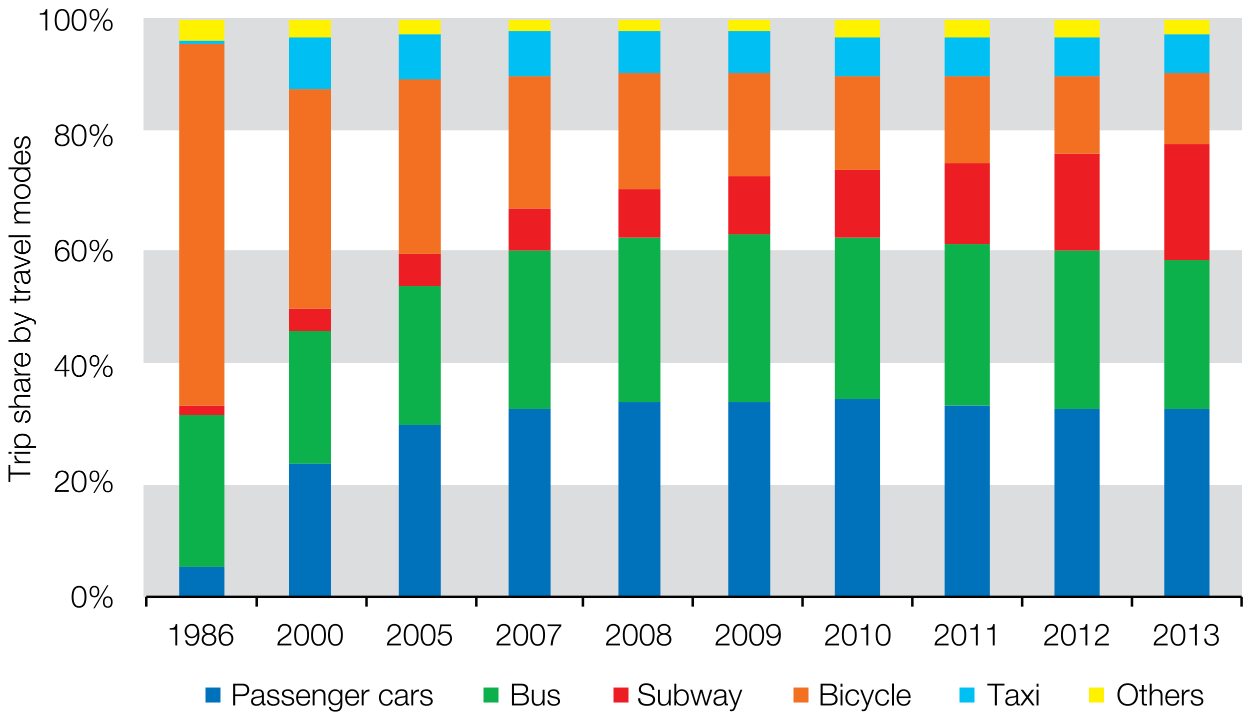


Figure 3.10 Travel mode shares of passenger trips in Beijing, 1986-2013

Source: Beijing Transportation Research Center, 2014

To control in-use high-emitters, such as yellow-labelled vehicles, trucks and motorcycles, Beijing has implemented a series of driving restrictions. Yellow-labelled vehicles have been prohibited from driving within the Second Ring Road since 2003; the ban was temporarily expanded to the entire city boundary during the Summer Olympics in 2008. Starting in January 2009, yellow-labelled vehicles are prohibited from driving within the Fifth Ring Road and in October 2009, the restriction was expanded to the Sixth Ring Road. Trucks have been banned within the Fourth Ring Road during the daytime, from 6 a.m. to 11 p.m. since February 2004; among them, trucks with vehicle weight of more than eight tonnes have not been allowed to drive on the main roads of the Fifth Ring Road from 6 a.m. to 10 p.m. since January 2004. Motorcycles are not allowed to drive inside the Fourth Ring Road (excluding its side roads).

To further limit the rapid growth of the vehicle population and high use-intensity and concentrated distribution in the urban areas for passenger cars, Beijing began to impose traffic control measures in October 2008 on the basis of needed temporary traffic control measures during the Summer Olympics in 2008. One such measure is the odd-and-even licence policy. Passenger cars are required to stop driving one weekday per week based on the last digit of their licence plates, which has become a long-term policy. Starting from January 2011, Beijing has further applied a licence control policy to limit total vehicle population. Issuing licence plates were based on a lottery system with a monthly quota of 20,000 additional plates (vehicles) from 2011 to 2013. In 2014, Beijing further tightened the quota of new vehicles to limit the total vehicle population below six million by 2017. The package of long-term and restrictive traffic measures implemented in Beijing has lowered the growth rate of vehicle population since 2010 (figure 1.3) and effectively alleviated the urban traffic pressure, as nearly 50 per cent of passenger trips are made by public transport. Furthermore, construction of parking space, intelligent traffic management, differentiated parking fees and management of vehicles registered in other provinces have also helped to optimize the urban travel mode share and reduce the dependence on passenger cars.

(6) Economic incentives

In recent years, Beijing has increasingly focused on the role of economic incentives and tools in reducing vehicle emissions. In 2008, the government of Beijing offered appropriate subsidies to retrofit nearly 10,000 heavy-duty diesel vehicles, which were in service as public transport, postal, sanitation, interprovincial tourism and construction vehicles. In August 2011, Beijing released a plan to further promote the elimination of older vehicles, offering economic incentives and encouraging the phasing out of non-public vehicles before they reach their mandatory scrappage time point. In late 2012, Beijing updated this plan with an amendment that: (1) placed the elimination of pre-China 3/III vehicles as a priority by promoting increased scrappage; (2) boosted the subsidy rate from 4,500 Chinese yuan (RMB) to RMB 6,500 for passenger cars; (3) encouraged vehicle manufacturers to provide flexible incentive to users to promote fuel efficient car models; and (4) provided additional subsidies to vehicle owners that switch to new energy vehicles. Over a three-year period from 2011 to 2013, 220,000, 380,000 and 370,000 older vehicles were annually phased out from the Beijing fleet, respectively. These figures greatly exceeded the originally planned targets.

3.3 Air quality monitoring, reporting and episode management

As improving air quality is a comprehensive and arduous task, it is necessary to establish a systematic monitoring and reporting system for both ambient air pollutant levels and major emission sources. A systematic monitoring and reporting system will contribute to making science-based decisions and developing cost-effective control measures. Beijing has focused on developing air quality monitoring networks, improving the accuracy and timeliness of air quality forecasting, performing source apportionment of $PM_{2.5}$, evaluating actual effects of air pollution control measures and building effective channels for information dissemination to enhance public participation.

(1) Development of ambient air quality monitoring network

In the 1980s, the first automatic air quality monitoring network in China was established in Beijing. The system, which is still operating, consists of eight stations located in the urban area to monitor Beijing ambient air quality status and to document the long-term trend. The monitoring stations can monitor CO, SO_2, NO_X, and TSP.

Since 1999, Beijing has expanded and enhanced the air quality monitoring network based on the spatial distribution and yearly changes of population, air pollution characteristics, industrial and economic development and other factors. Before the 2008 Summer Olympics (figure 3.11), the automatic ambient air quality monitoring network was comprised of 27 stations covering major parts of districts and counties; it has gradually shifted to primarily focus on particle measurements and added PM_{10} as one regulatory monitoring parameter. Quality assurance and quality control (QA/QC) has also improved by enhancing the capacity of technicians.

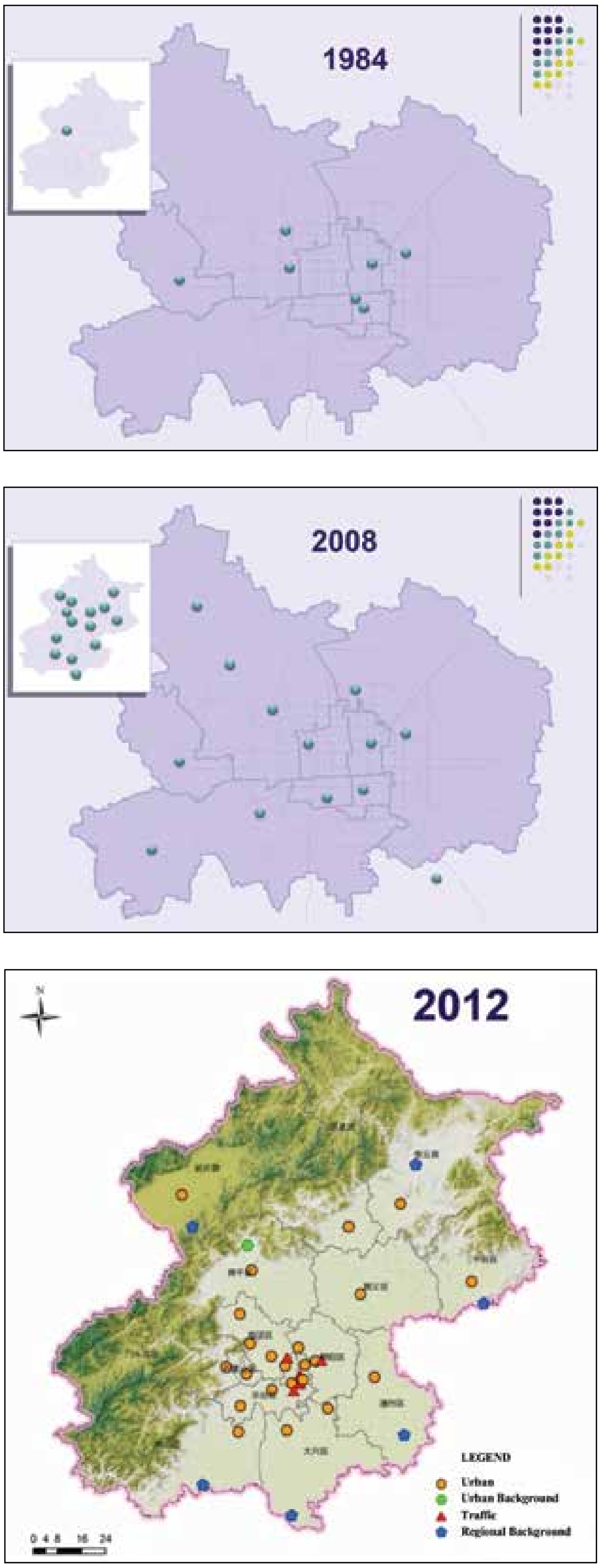


Figure 3.11 Evolution of the automatic ambient air quality monitoring system in Beijing

Source: Beijing Municipal Environmental Monitoring Center, 2012

To comply with the amended Ambient Air Quality Standard (GB3095-2012), since 2012, Beijing has expanded the automated air quality monitoring network to 35 stations, which are spatially distributed in the 16 administrative districts and counties, including in the economic-technological development zone (figure 3.11). At those stations four major monitoring functions are carried out: (i) urban air quality monitoring; (ii) background air quality monitoring, (iii) interprovincial transport contribution monitoring; and (iv) monitoring of traffic-populated roadsides. Ambient $PM_{2.5}$ concentration can be monitored at all of the stations. In addition to the automatic air quality monitoring stations, Beijing is applying advanced techniques to enhance its monitoring capability. For example, it has applied remote-sensing techniques, lidar measurement of aerosol vertical structure and comprehensive laboratory analysis of ambient samples. It has also continued to measure aerosol chemical speciation using online monitors. To summarize, Beijing has established a comprehensive monitoring system. A major component of this system is an automated monitoring network, which is supplemented by manual measurement and mobile monitoring. The system provides key information for policymakers and the public.

(2) Enhancement of air quality forecasting and reporting

On 1 May 2001, Beijing began to release to the public air quality forecast, which included projected index ranges and the pollution levels of three major pollutants, namely SO_2, NO_2, and PM_{10}. The air quality forecast was reported to the China National Environmental Monitoring Center and the National Meteorological Center, and released through Beijing television and radio stations.

During the 2008 Olympic preparations, air quality forecasting became an important task. Building on this, Beijing significantly improved its air quality monitoring network, monitoring capability and data analytical ability. Meanwhile, air quality forecasting and warning techniques have also been systematically upgraded. As a result, the air quality forecasting system in place in Beijing is comparable with those of most international megacities. It consists of three components: a statistical model; a numerical model; and an expert system (figure 3.12).

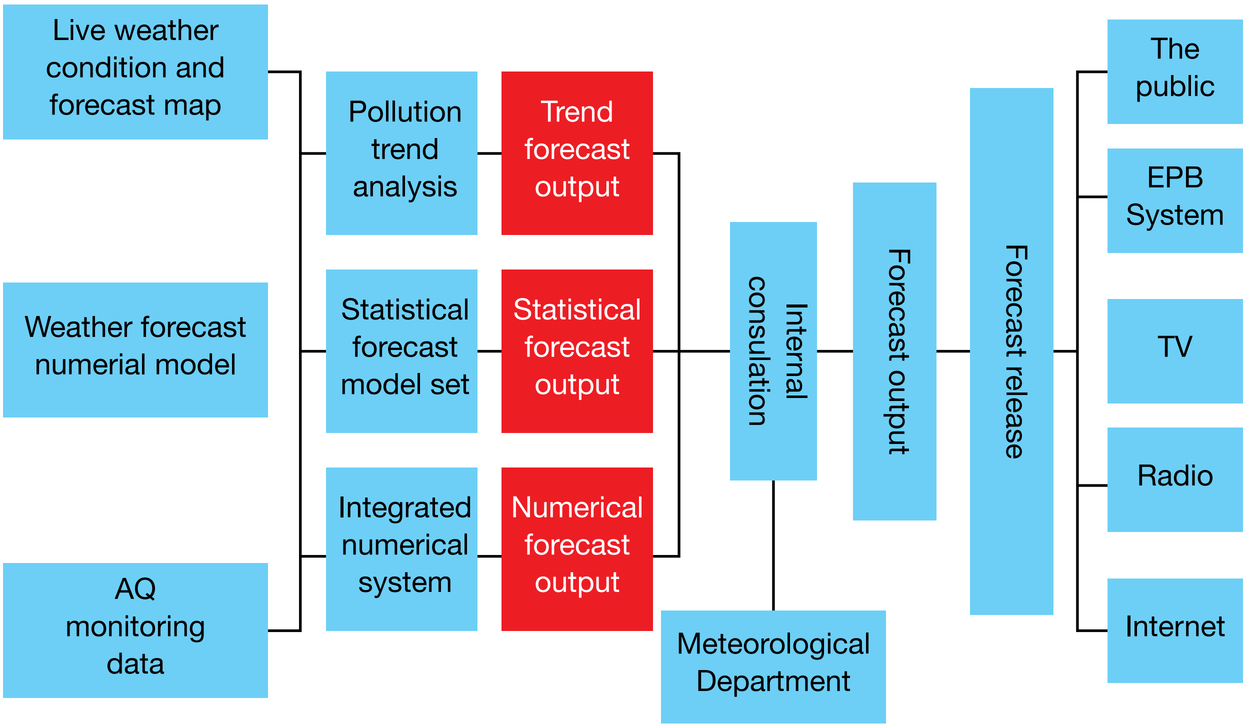


Figure 3.12 Technical and operation framework of air quality forecasting in Beijing

Source: Beijing Municipal Environmental Protection Bureau, 2008

The air quality monitoring network has enabled Beijing to steadily increase the frequency and improve the quality of its air quality data reporting. In 1998, the city began to release a weekly air quality report, which in 1999 became a daily report. Since 2001, Beijing has been releasing its air quality forecasts. In 2012, Beijing improved the release mechanism in accordance with the new NAAQS by: first, changing the daily averaged monitoring data to real-time hourly concentrations; second, changing from publishing city-averaged data to monitoring data from each station; and third, releasing to the general public, the ambient concentrations of all criteria of air pollutants instead of one major air pollutant with the objective to improve the reporting details.

Since January 2013, air quality forecasting products of Beijing have been following the Technical Regulation on Ambient Air Quality Index (AQI) (on trial) (HJ633-2012). A district/county-explicit information service for the six criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3) is now available, including the short-term forecast for the coming nighttime, the following daytime and for the next three days based on the AQI assessment system. In addition, for major events and holidays, additional potential changes of ambient air quality for the next 7 to 10 days are estimated based on meteorological data.

Figure 3.13 A smartphone application to check real-time Air Quality Index and concentrations of major air pollutants in Beijing

Photo credit: Beijing Municipal Environmental Monitoring Center

Real-time hourly concentrations of the criteria air pollutants, assessment results, health tips and air quality forecast information from the 35 monitoring sites have been available to the public since 2013. Beijing has set up multiple channels to release air quality information, covering not only traditional television and radio but also websites and important new media channels, such as Weibo, WeChat and smartphone applications (figure 3.13). For example, residents and travellers now can use the smartphone application Beijing Air Quality to obtain real-time air quality information, which allows them to properly adjust their activities and avoid health hazards associated with severe pollution.

(3) Improvement in emergency response regarding episode management

Due to its location of being surrounded by mountains on three sides and stagnant meteorological conditions several times each year, Beijing experiences air pollution episodes with high concentrations of air pollutants. Therefore, the city has developed an air pollution episode management programme. After initial pilot runs, the programme is being improved.

To alleviate the adverse impact from heavy haze episodes, such as their potential harm to public health, Beijing has periodically improved its emergency response mechanism to adopt temporary emission control measures and reduce pollution levels. The first Emergency Action Plan for Extreme Air Pollution Day in Beijing (for trial implementation) was published in October 2012. Summarizing the experiences and lessons learned from the operation of the action plan, and soliciting public opinion, Beijing have made two amendments to it, in 2013 and in 2015. The updates have improved substantially the management mechanism and optimized the pollution-level grading, and strengthened response control measures.

For example, the effects from winter heating, extreme weather conditions and regional transport of pollutants resulted in several heavy pollution episodes in Beijing during November and December 2015. According to the Emergency Plan for Extreme Air Pollution in Beijing, red alerts for heavy air pollution were issued twice between 8 and 10 December, and 19 and 22 December. During the red alert periods, some industrial plants limited or stopped production, outdoor construction activities were prohibited, vehicles were banned from roads on alternating days depending on the last digits of their licence plates, namely odd-even plate number traffic restrictions, and primary and middle schools and kindergartens were closed. Furthermore, coordinated emergency response actions were taken in surrounding provinces and cities. A preliminary evaluation indicated that approximately 30 per cent of emissions for major air pollutants, including SO_2, NO_X, PM_{10}, $PM_{2.5}$ and volatile organic compounds (VOC) were effectively avoided thanks to the implementation of the emergency response measures (Beijing Municipal Environmental Protection Bureau, 2015). In particular, those emergency measures slowed the accumulation rate of pollutants and reduced the pollution peak levels during the pollution episode (see figure 3.14).

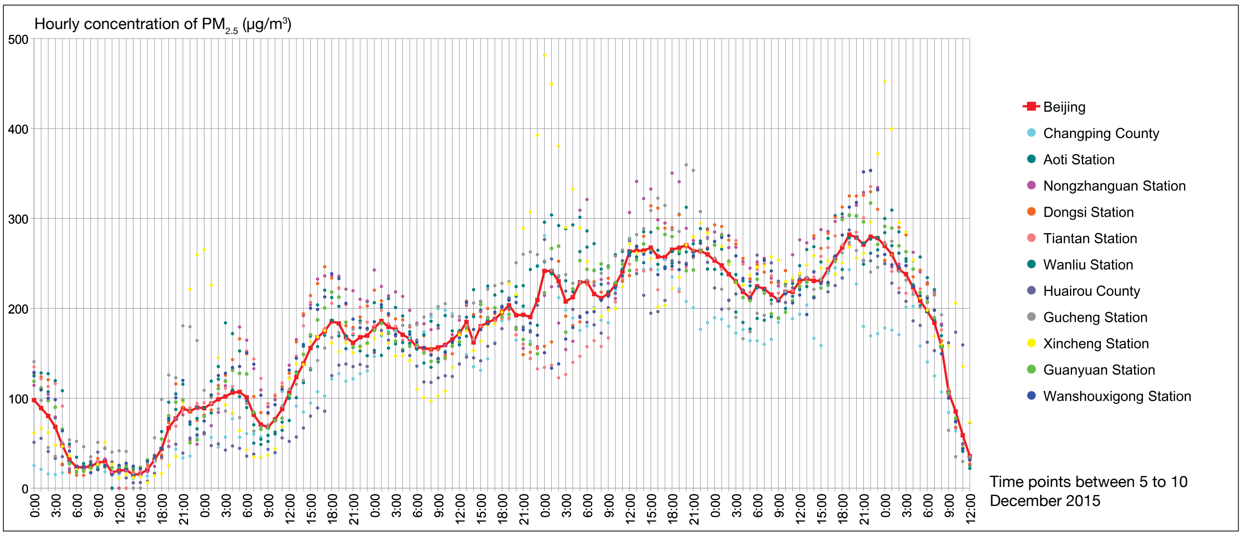


Figure 3.14 Hourly concentrations of $PM_{2.5}$ in Beijing, from 5 to 10 December 2015

Note: The red alert covered 8 to 10 December 2015

Source: Beijing Municipal Environmental Protection Bureau, 2015

(4) Monitoring and information disclosure of key emission sources

In 2011, Beijing began to establish an automatic online monitoring system for key pollution sources that focuses on key pollution sources at state and municipal levels. This system became operational in September 2014. Currently, it conducts real-time monitoring of major primary air pollutants, such as SO_2, NO_x and PM and the operating conditions for more than 40 manufacturing companies (with 88 monitoring sites) using video surveillance. The system has useful functions, including alarms for abnormal operating conditions and serving as a source for data queries and statistical analysis. As a consequence, a multiscale monitoring system, including the city, districts and key manufacturing companies is now operational and is effectively monitoring major emission sources in Beijing (see figure 3.15).

Figure 3.15 An example of the automatic real-time monitoring system interface for key pollution sources in Beijing

Photo credit: Beijing Municipal Environmental Protection Bureau

Chapter 4

Assessment on Avoided Emissions from Air Pollution Control Measures

4.1 Assessment method and modeling tool

(1) Assessment of avoided emissions from control measures on coal-fired sources

Control measures on coal-fired sources assessed in the study mainly include: replacement with clean energy, such as natural gas and the application of end-of-pipe control technologies in power plants; comprehensive controls on coal-fired boilers; and residential heating renovation. This study employs the Multi-resolution Emission Inventory for China (MEIC) model, which was developed by Tsinghua University to quantify emission reductions from control measures for coal-fired sectors. Based on a dynamic inventory technique and consistent data source, the MEIC model covers more than 700 sources, and is aggregated into several sectors, including, among others, the power, industry and residential sectors, with the emission factors derived on the basis of a large profile of local measurement results (Zhang et al., 2009; Lei et al., 2011).

For emission control on the power sector in Beijing, this study set up a "w/o control" scenario in which there were no end-of-pipe facilities or natural gas penetration combined with actual power generation to assess avoided emissions from the construction of end-of-pipe facilities, such as dedusting, desulfuration and denitrification, as well as the use of natural gas for power generation. For comprehensive control of coal-fired boilers, the study established the w/o control scenario to assess avoided emissions resulting from replacing natural gas in the three phases. For residential heating renovation, the study focuses on assessing the avoided emissions resulting from the replacement of residential coal consumption.

(2) Assessment on avoided emissions from control measures on vehicle emissions

Vehicle control measures assessed mainly included implementation of new vehicle emission standards, improvement in fuel quality, such as reducing sulfur content, an enhanced I/M programme, promotion of clean fuels and new energy vehicles, traffic measures, such as licence control and driving restrictions for light-duty passenger vehicles, economic tools, and scrappage of older vehicles. In this study, the Emission Factor Model for the Beijing Vehicle Fleet Version 2.0 (EMBEV 2.0) developed by Tsinghua University is applied to evaluate emission reduction benefits from upfront control measures (Zhang, 2014; Zhang et al., 2014a). Technically, the EMBEV model was developed based on dynamometer tests for more than 1,700 light-duty gasoline vehicles in Beijing over a variety of driving cycles, including the type-approval cycle, the typical cycle of Beijing and a suite of speed-specific cycles, and on-road tests for nearly 150 local heavy-duty diesel vehicles, such as buses and trucks, by using portable emissions measurement systems (PEMS). Therefore, this localized model is able to accurately simulate emission factors of major air pollutants for each technology group and each vehicle classification, and further calculate total vehicle emissions in Beijing (Wu et al., 2012; Zhang et al., 2014a and 2014b).

A series of uncontrolled scenarios have been designed using 1998 as the reference year. It should be noted that restrictive policies for yellow-labelled or older vehicles and encouragement of scrapping older vehicles with subsidies would significantly accelerate vehicle retirement compared to the natural scrappage rate without those policy interventions. For the sake of simplicity, the w/o control scenario involved in the study assumes that there is no vehicle retirement. The study takes into account vehicle scrappage, implementation of emission standards for new vehicles, improvement in fuel quality, an enhanced I/M programme, promotion of clean fuels and new energy vehicles, such as natural gas vehicles and battery electric vehicles, and the application of restrictive traffic management to assess itemized effects of upfront control measures.

4.2 Assessment of avoided emissions from adjusting urban energy structure and controlling coal sources

(1) Power plants

Despite a steady increase in total electricity demand (Beijing Municipal Statistics Bureau, 1998-2014), estimates indicate that the strict implementation of end-of-pipe control and the "Coal to Gas" strategy contributed to a continuous decline in $PM_{2.5}$ and PM_{10} emissions from power plants in Beijing from 1998 to 2013, while for SO_2 and NO_X emissions, they indicated trends in which the emission rose and then declined (figure 4.1). Compared with 1998, $PM_{2.5}$, PM_{10}, SO_2 and NO_X emissions from the power plants declined by 14,500 tonnes, 23,700 tonnes, 45,000 tonnes and 30,900 tonnes, in 2013, representing decreases of 86 per cent, 87 per cent, 85 per cent and 64 per cent, respectively.

Compared with the w/o control scenario, air pollution control measures adopted by power plants is estimated to have avoided $PM_{2.5}$, PM_{10}, SO_2 and NO_X emissions in 2013 by 85 per cent, 86 per cent, 87 per cent and 74 per cent, respectively (figure 4.1). As the control history of $PM_{2.5}$ and SO_2 emissions is longer than that of NO_X, benefits from $PM_{2.5}$ and SO_2 emissions control are more prominent.

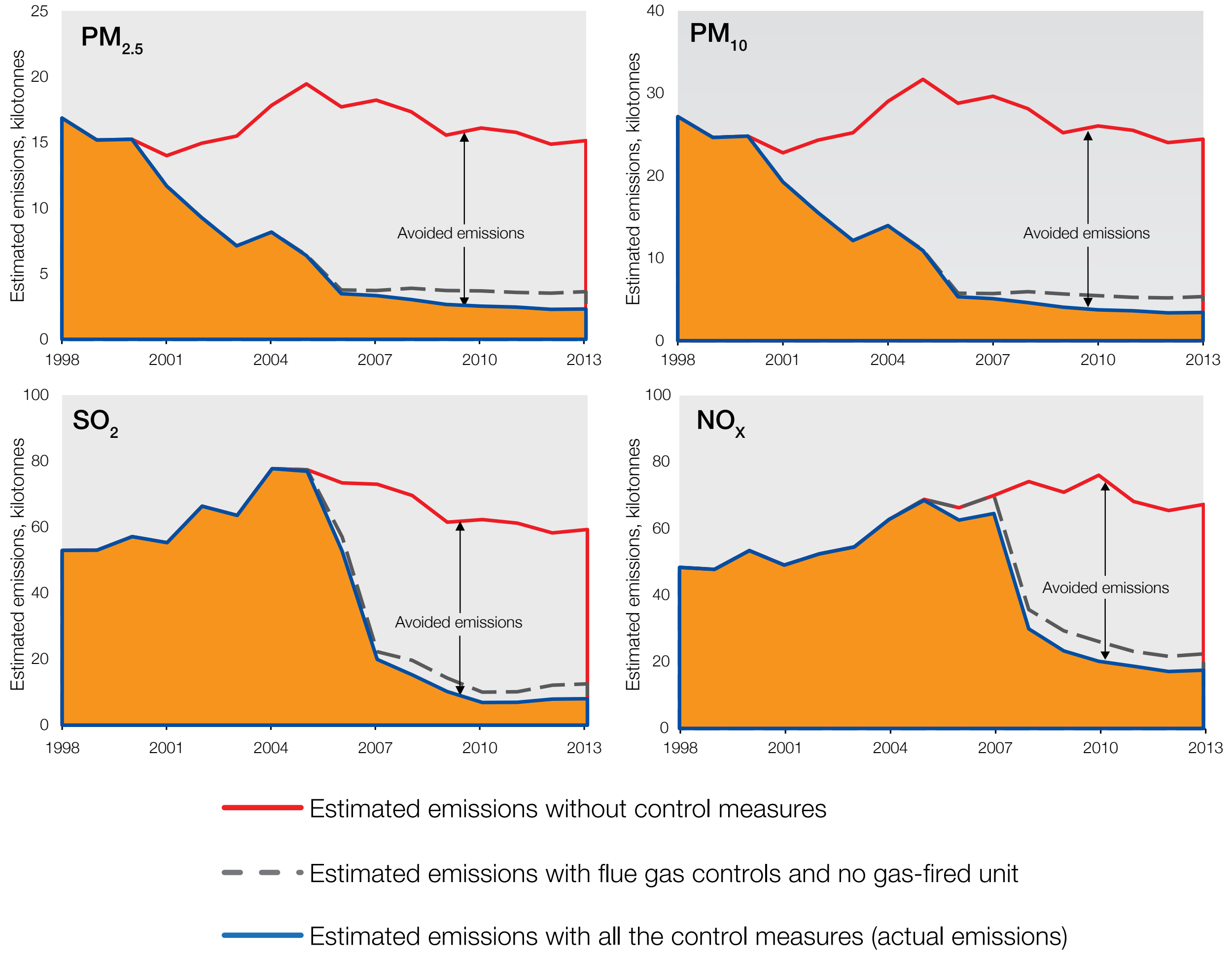


Figure 4.1 Assessment of avoided emissions from measures on power plants, 1998-2013

Among the emission control measures implemented, the application of end-of-pipe facilities such as electrostatic precipitators (ESP)/fabric filter, wet limestone-gypsum flue gas desulphurization (FGD) and selective catalytic reduction (SCR) play an important role in reducing emissions from power plants. In 2013, for example, compared with the w/o control scenarios, end-of-pipe control measures taken by Beijing power plants resulted in reductions of 11,500 tonnes of $PM_{2.5}$, 19,100 tonnes of PM_{10}, 46,700 tonnes of SO_2 and 44,900 tonnes NO_X, or of 83 per cent, 85 per cent, 85 per cent and 68 per cent, respectively (indicated as the gaps between red lines and gray dashed lines in figure 4.1).

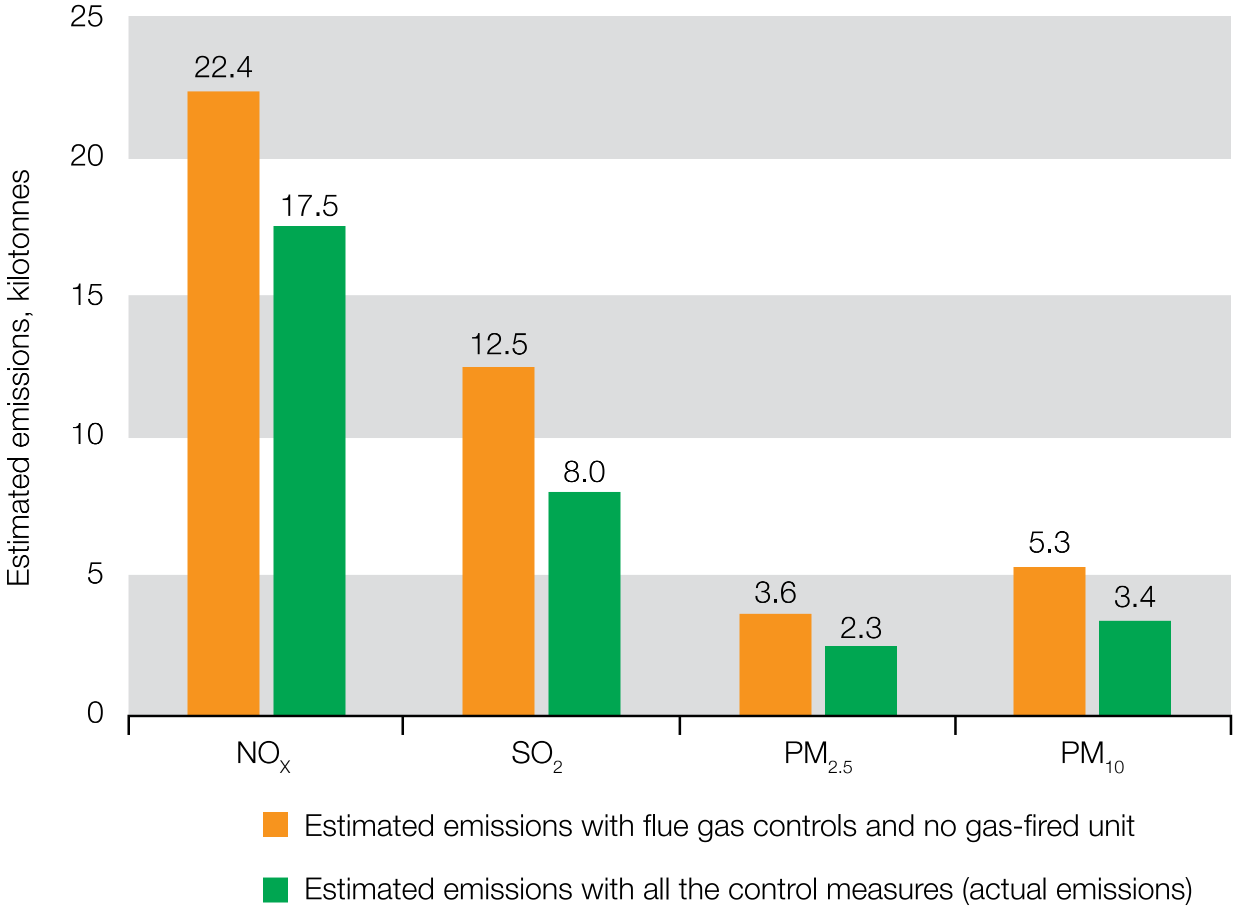


Figure 4.2 Assessment of avoided emissions from the "Coal to Gas" strategy for Beijing's power plants

The switch from coal to gas enables further emission reductions from power plants. For example, the replacement of coal-fired power units with natural gas turbines is estimated to have reduced 1,315 tonnes, 1,936 tonnes, 4,531 tonnes and 4,866 tonnes of $PM_{2.5}$, PM_{10}, SO_2 and NO_X, respectively, in 2013.

(2) Coal-fired boilers

In total, 14,300 tonnes of $PM_{2.5}$, 24,000 tonnes of PM_{10}, 136,000 tonnes of SO_2 and 48,700 tonnes of NO_X emissions were avoided because of the comprehensive control measures on coal-fired boilers undertaken from 1998 to 2013 (figure 4.3). Compared with estimated avoided emissions from power plants, $PM_{2.5}$ and PM_{10} emission reduction benefits from control measures adopted for coal-fired boilers were comparable, while the SO_2 and NO_X emission reduction benefits were much greater.

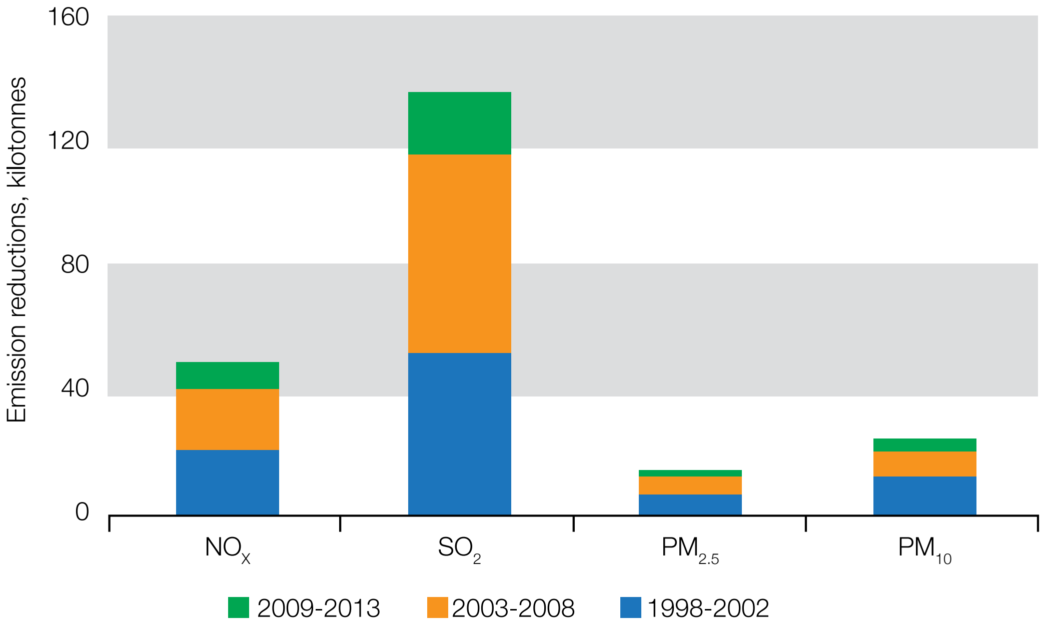


Figure 4.3 Avoided emissions from comprehensive control measures on coal-fired boilers in Beijing, 1998-2013

Centralized heating centres built in suburban districts/ counties to replace scattered small coal-fired units were also effective in reducing emissions of major air pollutants during the period 2006-2010. For example, Shunyi District shut down scattered small coal-fired boilers with a total scrapped capacity of 1,365 MW and built centralized and high-efficient coal-fired boilers with a total capacity of 1,120 MW during that period. This renovation project resulted in lower emissions of $PM_{2.5}$, PM_{10}, SO_2 and NO_X by 88 tonnes, 189 tonnes, 925 tonnes and 895 tonnes, respectively (figure 4.4). It should be noted that coal demand in some districts, such as Changping, continued to increase after those residential heating renovation projects were completed, as many large-scale residential communities were established outside the Fifth Ring Road with the surge of urban development in Beijing. Higher capacity of centralized heating centres compared with scattered coal-fired boilers considerably offset SO_2 and NO_X emission reductions.

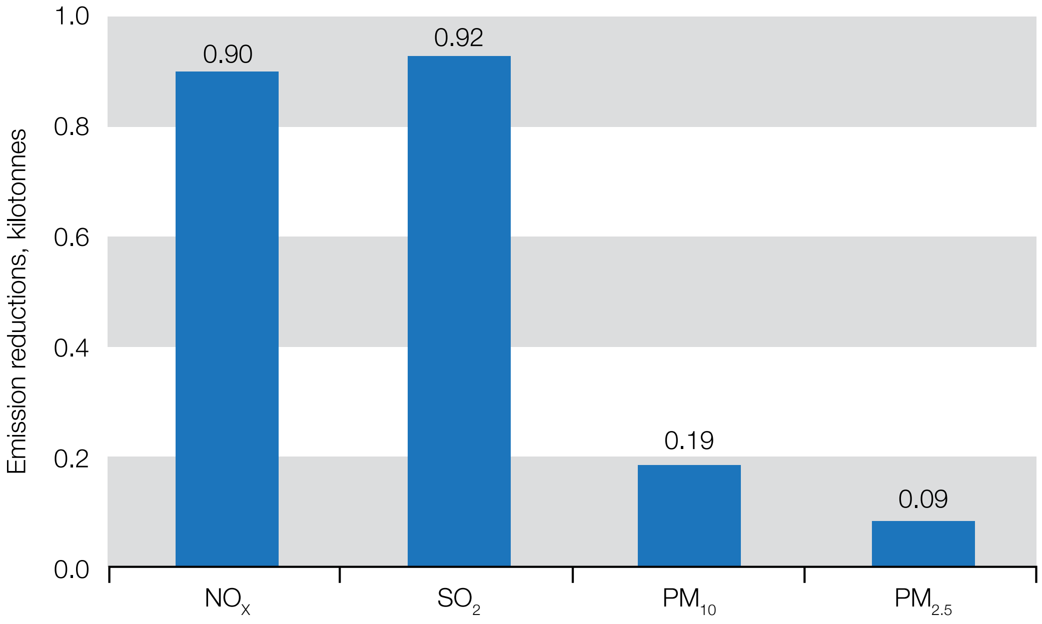


Figure 4.4 Emission reductions contributed by centralized heating centres in Shunyi District, 2006-2010

(3) Residential heating

Residential heating renovation projects that entailed replacing coal with electricity in the conventional old house areas of Beijing were mainly conducted in two stages from 2003 to 2013, and contributed to emission reductions of 630 tonnes of $PM_{2.5}$, 870 tonnes of PM_{10}, 2070 tonnes of SO_2 and 790 of NO_X (figure 5.5).

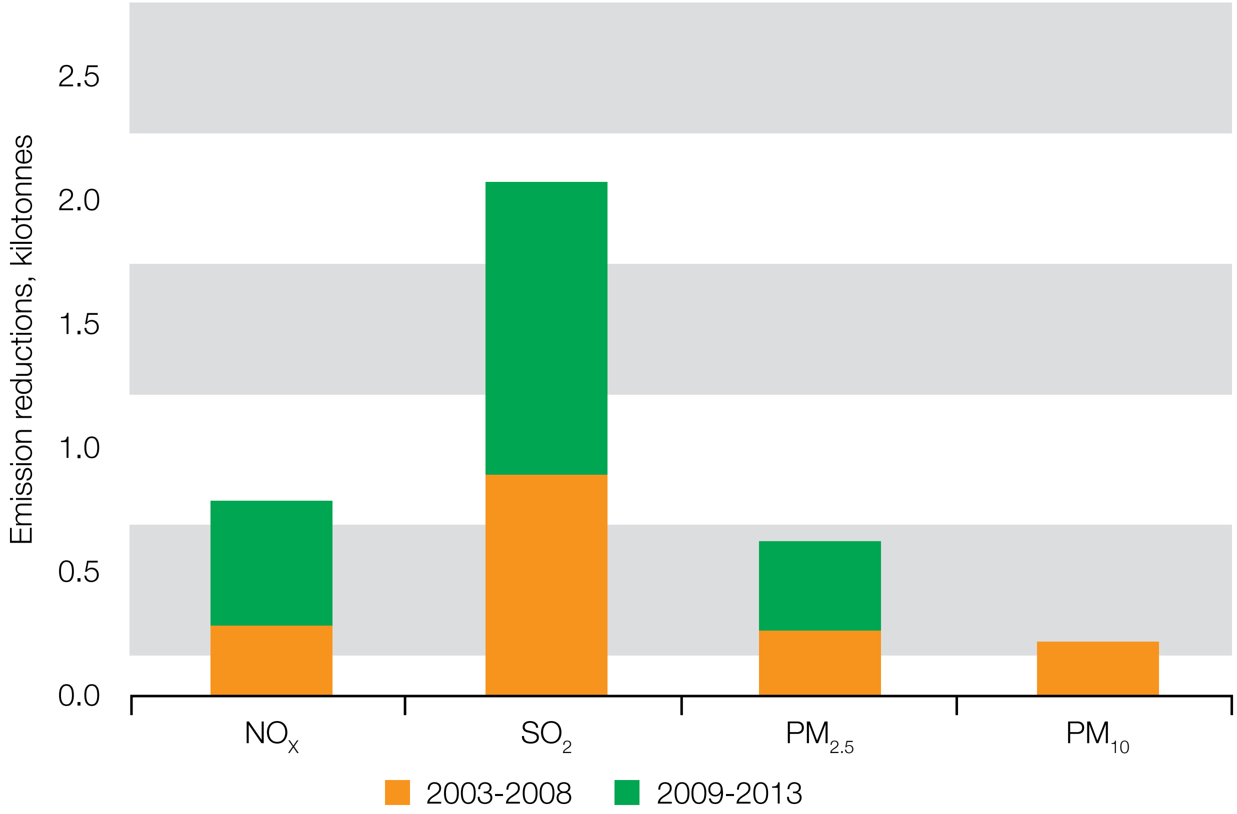


Figure 4.5 Avoided emissions from residential heating renovation by replacing coal with electricity in the conventional old house areas of Beijing from 1998 to 2013

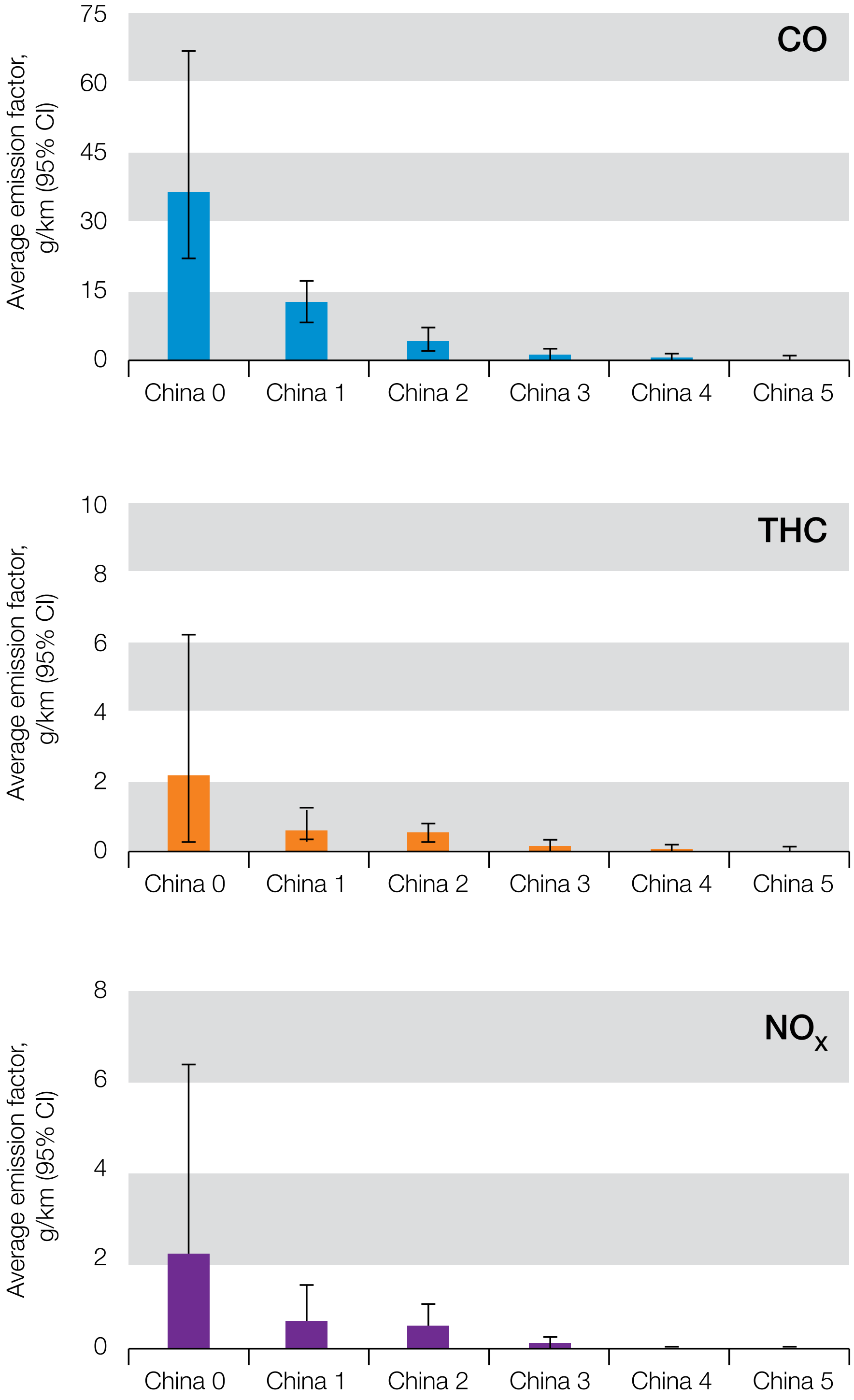
Emission reductions from the residential heating renovation in old one-storey house areas have been relatively small when compared with emission controls on coal-fired power plants and boilers. However, taking into consideration the dense layout and large population in those old house areas, the renovation project may have: significantly improved air quality during heating seasons; lowered indoor exposure levels of coal-fired pollutants; and improved the living quality and security levels of the residences. Therefore, the environmental and health benefits from renovating heating systems in the old one-storey house area may actually be quite significant.

4.3 Emission reduction benefits from controlling vehicle emissions

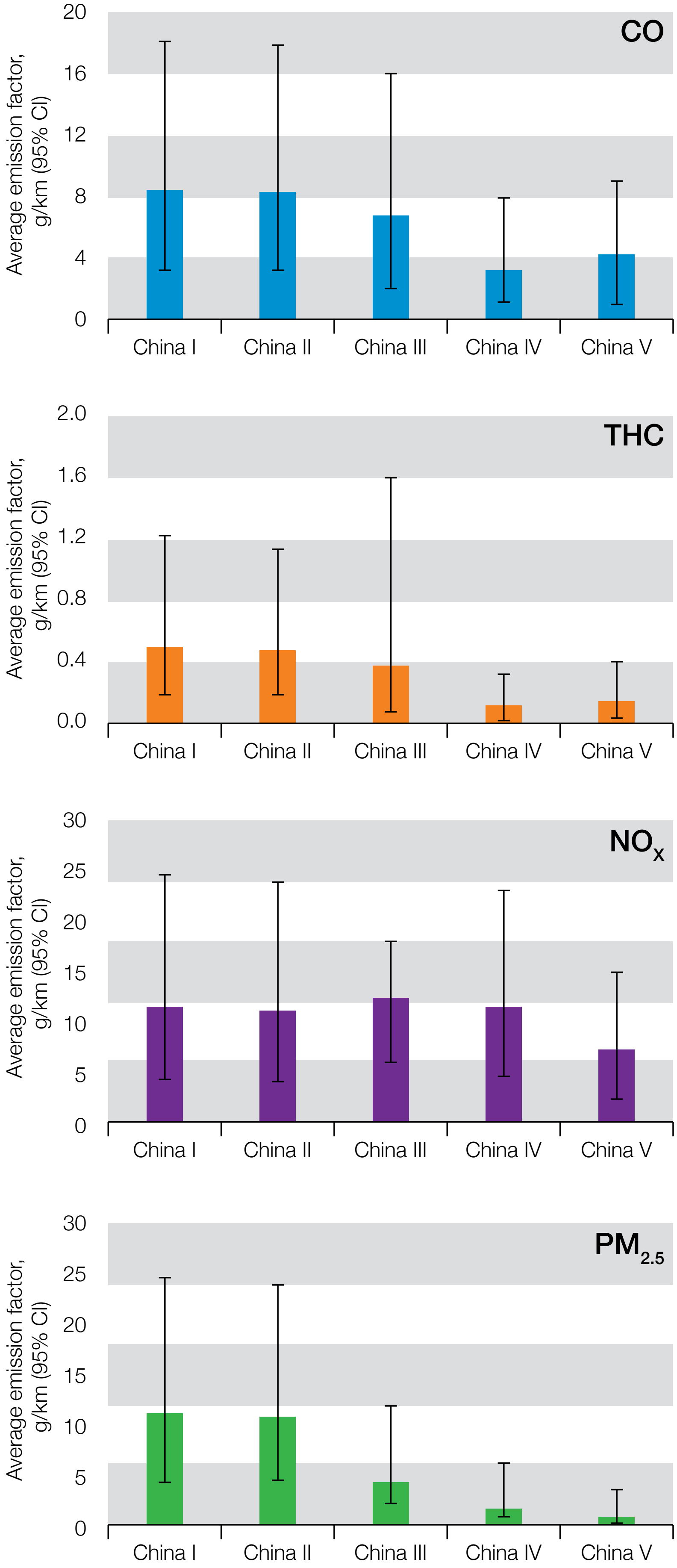
(1) Pollutant emission factors of motor vehicles

The EMBEV model shows that increasingly stringent emission standards have effectively reduced emission factors of light-duty gasoline vehicles. In general, each tightening of emission standards, such as from pre-China 1 to China 4, contributes 50 to 70 per cent emission reductions of gaseous pollutants (figure 4.6). Currently, emission factors of light-duty gasoline vehicles complying with the China 5 are 0.46 g/km for CO, 0.09 g/km for THC and 0.018 g/km for NO_X (Zhang et al., 2014a). In other words, emissions from a pre-China 1 gasoline car are almost equivalent to those from 50-100 China 5 gasoline cars.

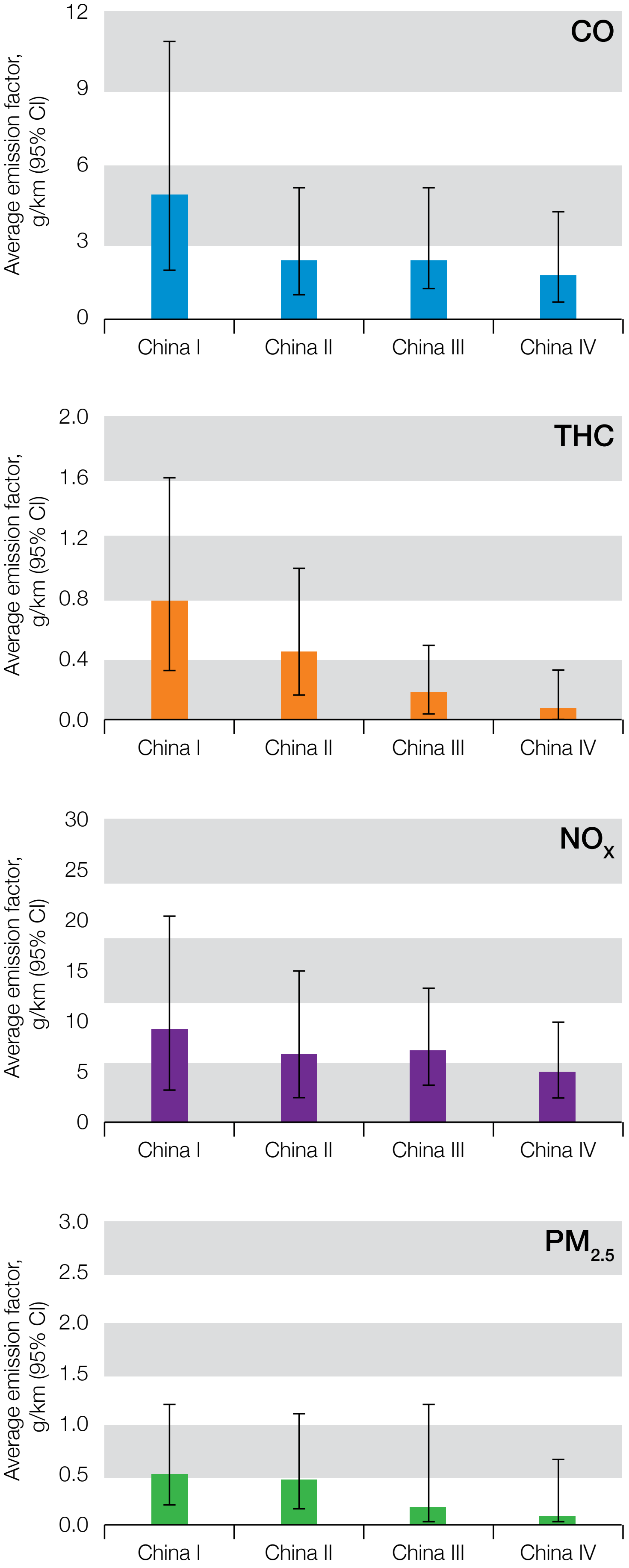
The tightening of emission standards has also resulted in significant reductions in emission factors of CO, THC and $PM_{2.5}$. For example, the average $PM_{2.5}$ emission factor for China V diesel buses is up to 90 per cent lower than the standard for their China I counterparts. However, while some data indicate improvements under highway driving conditions, NO_x emission factors of heavy-duty diesel vehicles have not improved significantly or to the level expected after emission certification levels become more stringent. For urban diesel buses, although they have adopted SCR devices as required under the China IV stage, low exhaust temperature under congested urban driving conditions leads to unsatisfactory NO_x emission control in the real world (figure 4.6) (Wu et al., 2012).



i. Emission factors of light-duty gasoline vehicles



ii. Emission factors of diesel public buses



iii. Emission factors of heavy-duty diesel trucks (gross vehicle weight over 12 tonnes)

Figure 4.6 Emission factors for each vehicle technology group in Beijing: light-duty gasoline vehicles, diesel public buses and heavy-duty diesel trucks

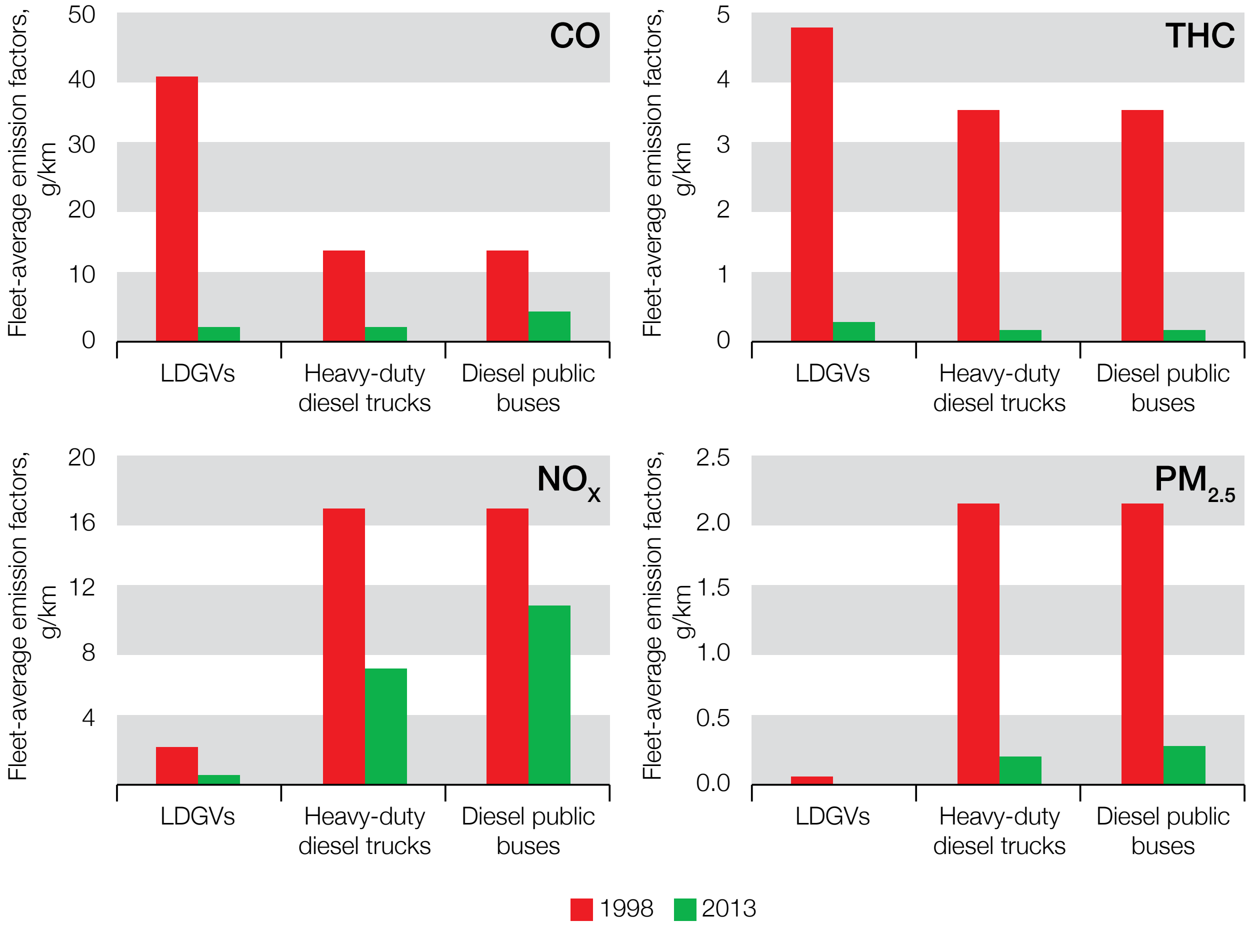


Figure 4.7 Fleet-average emission factors of typical vehicle classifications in Beijing, 1998 and 2013

Abbreviation: LDGVs, Light-duty gasoline vehicles

It is worth noting that recent studies in Europe have also revealed similar difficulties in reducing real-world NO_X emissions from heavy-duty diesel vehicles (HDDVs) (Carslaw et al., 2011; Velders et al., 2011). This can be primarily attributed to the following aspects. First, in the engine combustion process, there can be a trade-off between fuel efficiency and NO_X emission control. As customers are more aware of and interested in good fuel efficiency, engine manufacturers tend to limit NO_X control as narrowly as possible to pass the type-approval test. As a result, NO_X emissions tend to be much higher for driving conditions that are not covered by the type-approval test. Second, the type-approval test cycles adopted in Europe and China are heavily weighted towards high speed, high-load driving conditions rather than typical urban driving. As a consequence, NO_X emissions in urban driving conditions have not improved when type approval is solely based on current regulatory cycles. Furthermore, the problem is compounded with Euro IV and Euro V HDDVs because the most effective NO_X control technology used by most manufacturers is SCR, which is effective in reducing NO_X emissions in actual operation but a high exhaust temperature must be achieved. Unless engine manufacturers make a special effort to design their systems to reach such temperatures under light loads and speeds typical in urban driving, most HDDVs undergoing the EU type-approval system will not achieve those activation temperatures under urban driving.

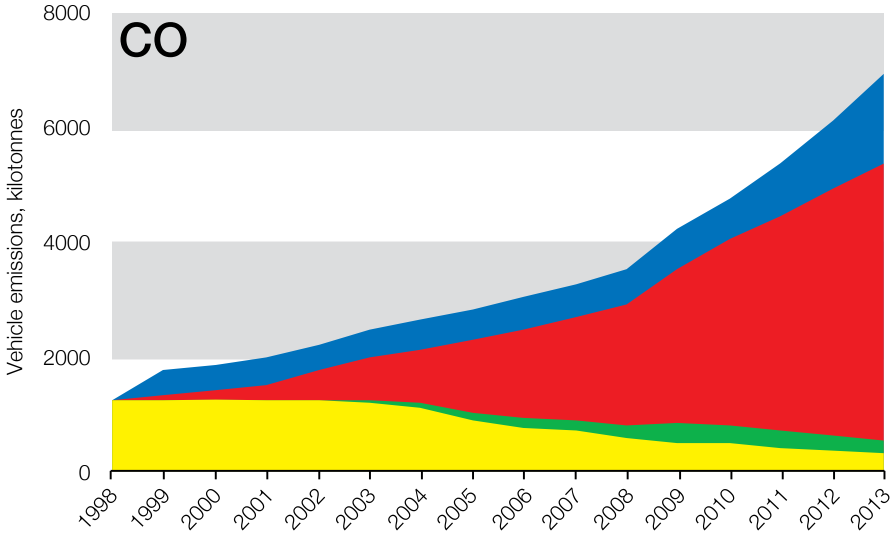
In 2012 and 2013, the Beijing EPB took steps to become much more proactive in addressing this problem. First, it modified the vehicle registration system to assure that before any new vehicles were registered in Beijing, they must have the appropriate emissions control components, identical to those on vehicles and engines during the type-approval process. Second, it altered the type-approval test procedure, by adding a special urban test cycle and enabled the PEMS testing method (Beijing Municipal Government, 2013). Finally, it worked with manufacturers to reflash the computer chips on existing vehicles with the objective to improve the actual in-use NO_X emissions control in typical urban driving. This procedure has significantly improved NO_X emissions performance in the United States of America (California Environmental Protection Agency, 2010).

Compared with 1998, fleet-average emission factors of CO, THC and NO_X for light-duty gasoline vehicles in 2013 declined by 93-94 per cent, representing annual reductions of more than 15 per cent (figure 4.7). Given that emission levels of light-duty vehicles in Beijing are now very close to those in the United States and in European countries, Beijing has leapfrogged the steps for improving emission factors and is controlling emissions from light-duty gasoline vehicles by drawing on foreign experience. With regard to heavy-duty diesel vehicles, average $PM_{2.5}$ emission factors for buses and trucks in 2013 were down 85-90 per cent from 1998, with annual reductions of up to 14 per cent. Nonetheless, Beijing is still facing challenges to control on-road NO_X emissions from heavy-duty diesel vehicles.

(2) Trends in total vehicle emissions and avoided emissions

Estimates indicate that total vehicle emissions in Beijing dropped significantly during the period 1998-2013 on the back of integrated vehicle emission control measures. Compared with 1998, total vehicle emissions of CO, THC, NO_X and $PM_{2.5}$ in Beijing were mitigated by 76 per cent, 72 per cent, 40 per cent and 70 per cent, respectively (as illustrated by the yellow part in figure 4.8). Emission reductions of CO and THC mainly benefited from control measures adopted for light-duty gasoline vehicles, while the lower $PM_{2.5}$ emissions could be mainly attributed to control measures for HDDVs. However, the proportion of NO_X emission reductions is less than other pollutants.

Under the w/o control scenario, namely without consideration of the natural retirement of vehicles, vehicle ownership would keep rising and traffic conditions would become worse. In 2013, CO and THC emissions under the w/o control scenario were estimated to be about 20 times that of the estimated emissions under the scenario with control measures, while NO_X and $PM_{2.5}$ emissions were about 10 times the estimated emissions with control measures. As a result, relative to the w/o control scenario, CO, THC, NO_X and $PM_{2.5}$ vehicle emissions in Beijing were estimated to have been avoided by 96 per cent, 95 per cent, 88 per cent and 92 per cent, respectively, in 2013 (as the sum of the blue, red and green parts shown in in figure 4.8).



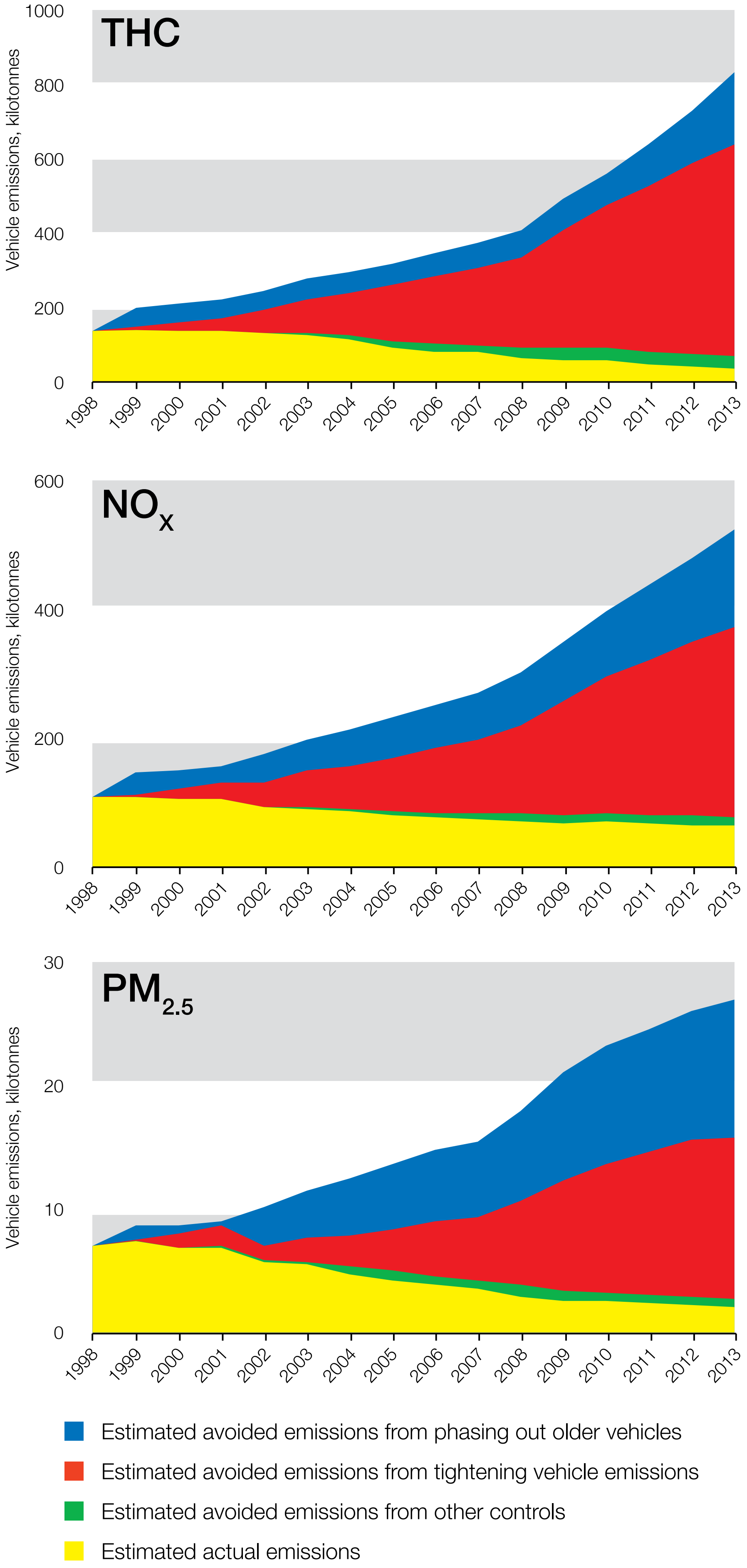


Figure 4.8 Estimated reductions in vehicle emissions in Beijing, 1998-2013

Considering that vehicle emissions are viewed as a major source of local ambient CO and NO_2 concentrations, such as 74 per cent of CO and 67 per cent of NO_2 concentrations, as reported by Hao et al. (2000), this study compares trends in estimated total vehicle emissions of CO and NO_X and annual concentrations of CO and NO_2 from 1998 to 2013 (figure 4.9). The average annual CO concentration in Beijing dropped from 3.3 mg/m^3 in 1998 to 1.4 mg/m^3 in 2012, a reduction of 58 per cent; while the reduction of NO_2 declined more moderately, by 30 percent, from 74 μg/m^3 in 1998 to 56 μg/m^3 in 2013 (Beijing Municipal Environmental Protection Bureau, 1998-2014). The correlation coefficients of vehicle emissions and annual ambient concentrations are as high as 0.92 for CO and 0.87 for NO_X/NO_2, providing proof for the contribution of mitigated CO and NO_X emissions from integrated vehicle emission control measures to the improvements in the concentration of CO and NO_2 in Beijing.

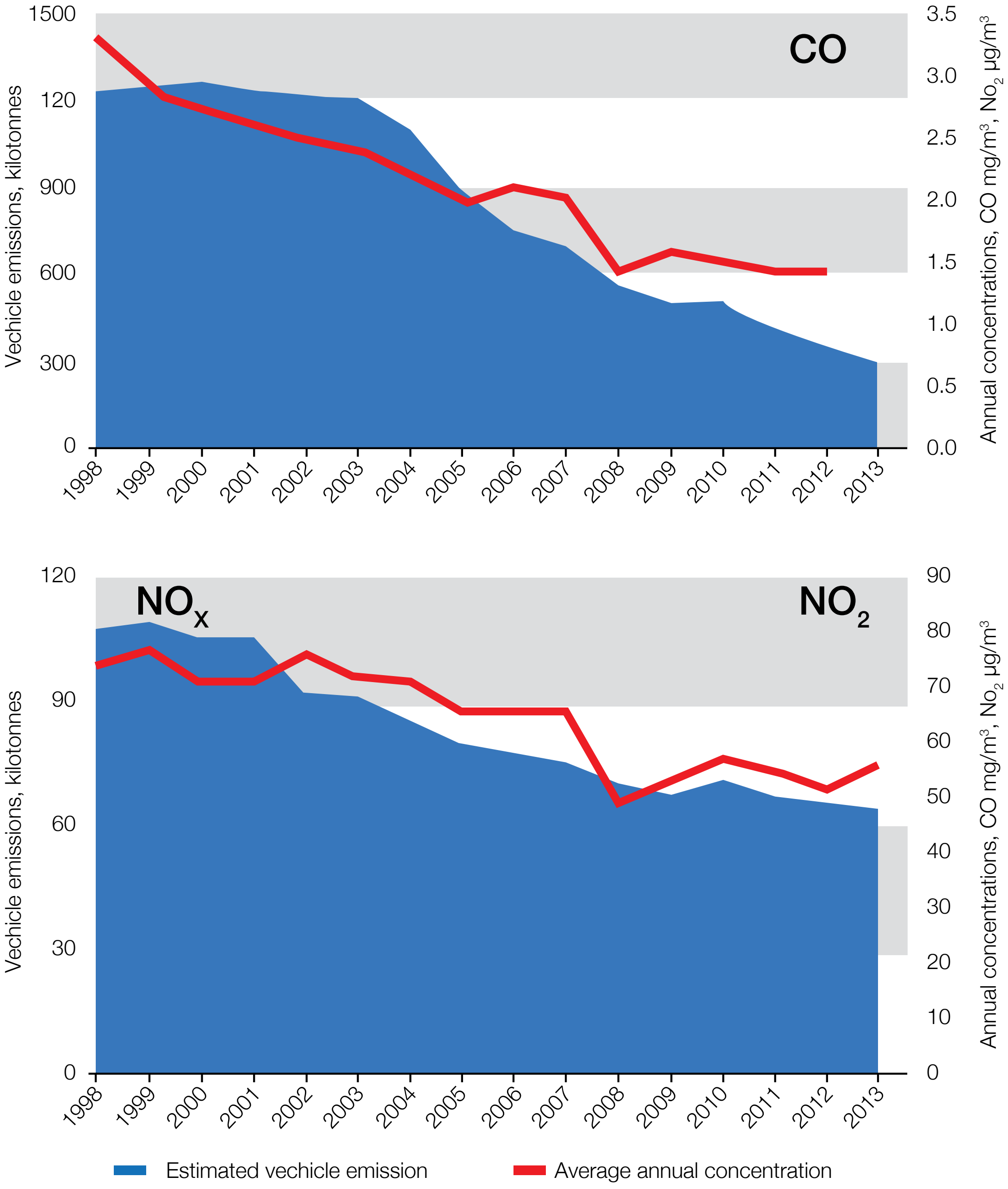


Figure 4.9 Comparison between estimated vehicle emissions and annual ambient concentrations for CO and NO_X/NO_2 in Beijing, from 1998 to 2013

Note: The monitoring metric of ambient CO concentration has changed according to the new NAAQs. As a result, the annual concentration of CO in 2013 is not presented in this figure.

(3) Emission reduction benefits from vehicle scrappage

This study further observes the effect of scrapping older or yellow-labelled vehicles, as shown in figure 4.8, relative to the w/o control scenario under which there is assumed to be no natural retirement of vehicles in Beijing. Compared with the w/o control scenario, scrappage programmes and incentives in Beijing are estimated to have avoided vehicle emissions of CO, THC, NO_X and $PM_{2.5}$ by 23 per cent, 23 per cent, 33 per cent and 45 per cent, respectively, in 2013.

Since 2008, driving restrictions on yellow-labelled vehicles have become stricter and economic incentives for phasing out older and yellow-labelled vehicles and advanced on-road inspection methods, such as remote sensing, have encouraged scrappage. Although it is very difficult to accurately quantify emission reductions resulting from recent control measures, this study has demonstrated that emission control benefits from vehicle scrappage in 2013 were much more substantial than those before 2007. The enhanced emission reductions are expected to be the result of restrictive traffic management and economic incentives to accelerate fleet turnover in Beijing.

(4) Avoided emissions from emission standards for new vehicles

This study has demonstrated that implementation of emission standards for new vehicles was the most effective measure to control vehicle emissions during the period 1998-2013. Relative to the w/o control scenario, tightening emission standards avoided emissions of CO, THC, NO_X and $PM_{2.5}$ by 73 per cent, 72 per cent, 64 per cent and 52 per cent, respectively, in 2013, as shown in figure 4.8.

(5) Avoided emissions from other major controls

Taking the year 2012 as a case study, this study has analysed avoided emissions from other measures implemented in Beijing. These measures include: improvement in fuel quality, an enhanced I/M programme; promotion of clean fuels and new energy vehicles that were primarily deployed by the public bus fleet; and traffic control measures, including the licence control policy and driving restrictions for light-duty vehicles (figure 4.10). Total avoided emissions of CO, THC, NO_X and $PM_{2.5}$ from those measures were 292,000 tonnes, 32,000 tonnes, 14,000 tonnes and 670 tonnes, respectively.

With regard to improvement in fuel quality, emission reduction benefits are achieved when vehicle emission standards are relatively loose, as with pre-China 2, accounting for 50 to 70 per cent of total avoided emissions from the measures mentioned above (figure 4.10). Under the enhanced I/M programme to reduce vehicle emissions, CO and THC emissions declined by about 10 per cent. As the public bus fleet is an important contributor to NO_X emissions, promoting clean fuels and clean energy vehicles resulted in avoided emissions of 20 per cent for NO_X. It should be noted that a majority of the natural gas buses in Beijing are equipped with lean-burn engines and have no dedicated after-treatment devices for NO_X emission control. If stoichiometric spark-ignition engines were to be promoted in public buses that also adopted three-way catalyst or SCR, more NO_X emissions could be mitigated from natural gas buses. Finally, restrictive traffic management, such as licence control and driving restrictions for passenger cars, implemented after the Summer Olympics accounted for avoided emissions of 25 per cent for CO, 31 per cent for THC, 31 per cent for NO_X and 17 per cent for $PM_{2.5}$.

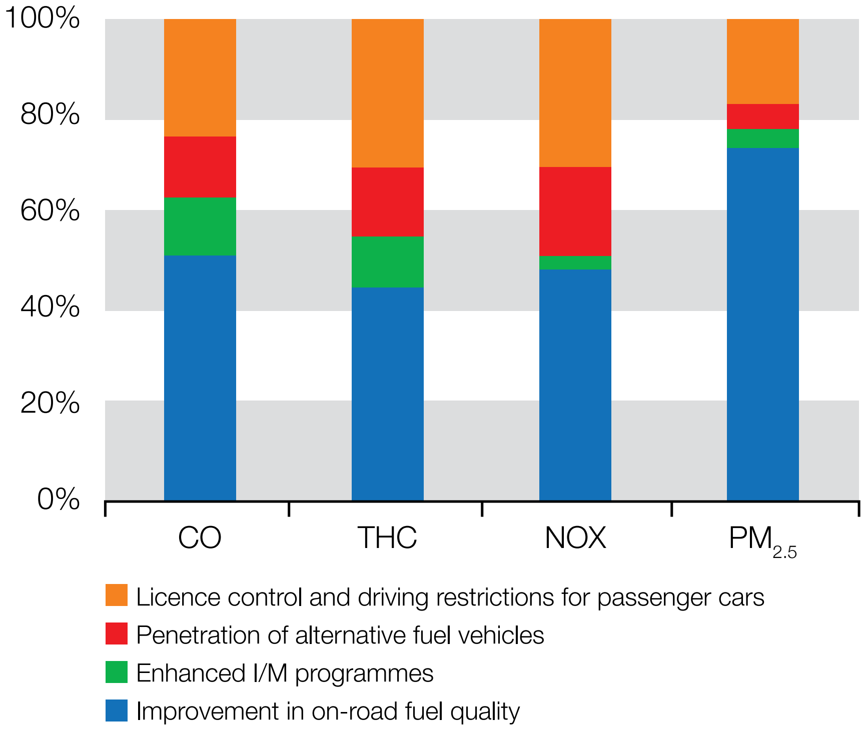
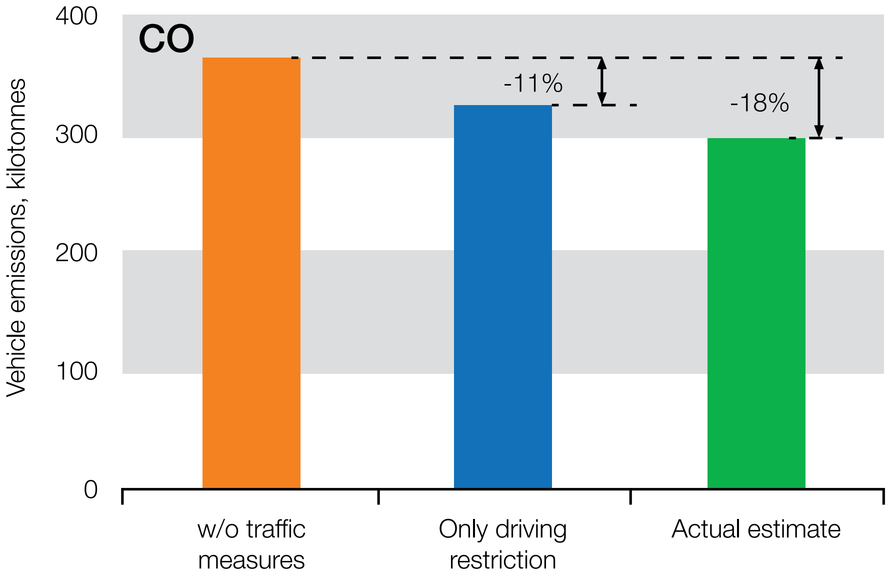


Figure 4.10 Avoided emissions from measures additional to vehicle scrappage programmes and new vehicle emission standards, 2012

(6) Emission reduction benefits from traffic management measures

After the Summer Olympics in 2008, Beijing implemented restrictive traffic management measures to limit the excessively rapid increase in the vehicle population and ease traffic operating pressures during rush hours. In 2013, the total vehicle population in Beijing reached 5.3 million, which, according to estimates, would have been 1.2 million higher if the timely licence control policy had not been implemented (Zhang et al., 2014a). Furthermore, based on real traffic flow data, the annual-average speed for passenger cars was 28 km/h, which was also elevated by nearly 10 per cent compared to the assumed scenario without driving restrictions (Zhang et al., 2014a). Thus, these two restrictive traffic measures are estimated to have reduced total vehicle emissions of CO, THC, NO_x and $PM_{2.5}$ by 18 per cent, 21 per cent, 6.2 per cent and 6.1 per cent, respectively, as of 2013 (figure 4.11).



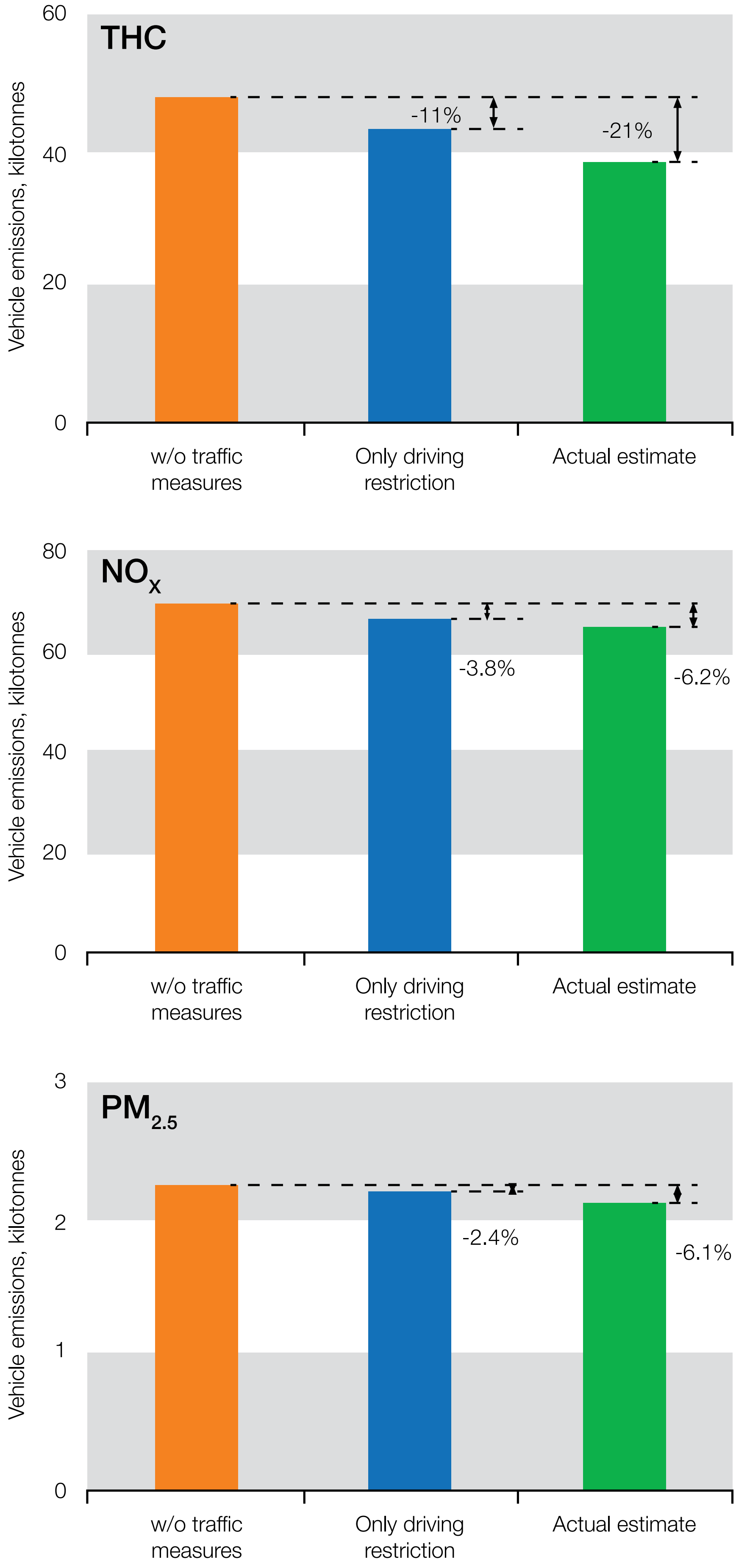


Figure 4.11 Avoided emissions from the licence control and driving restrictions on light-duty passenger vehicles in Beijing, 2013

Chapter 5

Achieving Air Quality for the 2008 Summer Olympics and the 2014 APEC Summit

Beijing has placed high priority on ensuring better air quality for major events. In this chapter, two case studies centred on the 2008 Summer Olympics and the 2014 APEC Summit illustrate how Beijing has implemented comprehensive measures to provide better air quality during major events.

5.1 Air quality for the 2008 Summer Olympics: a focus on vehicle emission control measures

The 2008 Summer Olympic Games in Beijing were the focus of worldwide attention (figure 5.1). To fulfil environmental commitments made in the bid to hold the Olympics, guaranteeing the air quality during the event with unique features became an essential component. On the basis of previous air pollution control measures, more intensified actions covering six major fields were undertaken during the Olympic Games and the following Paralympic Games in three phases, including strengthening vehicle emission control, and strict reduction of emissions from key production processes and polluting plants (Tsinghua University, 2009; Wang et al., 2010).

Figure 5.1 Beijing during 2008 Summer Olympics

Photo Credit: Beijing Municipal Publicity Center for Environmental Protection

This report analyses the temporary traffic management measures set during the Summer Olympics as a case study. Traffic management was one of the most important items required under the Plan for Guaranteeing the Air Quality during the Beijing Olympic Games. It was covered under a public notice issued by the government of Beijing on temporary traffic control measures for Beijing-registered motor vehicles during the 2008 Summer Olympic and Paralympic Games. The following was stated in the notice: (1) vehicles issued with yellow labels shall be banned from the road within the Beijing administrative region from 1 July to 20 September 2008; (2) an odd-and-even licence plate rule shall be implemented for vehicles from 20 July to 20 September 2008. The odd-even traffic restrictions apply to the whole Beijing administrative region from 20 July to 27 August 2008, and the area within the Fifth Ring Road (inclusive) from 28 August to 20 September 2008; (3) freight vehicles shall be banned from the area within the Sixth Ring Road (excluding the Sixth Ring Road) from 6 a.m. to 12 p.m.; (4) 30 per cent of government-owned vehicles shall be excluded from the road additionally starting earlier than 20 July , and consequently, the total proportion of their reduced activity could reach 70 per cent when added to the odd-even restrictions (Beijing Municipal Government, 2008). Those temporary measured affected several factors relating to the traffic flow in Beijing, such as fleet composition, traffic conditions and total vehicle activity (table 5.1).

Table 5.1 Influencing factors in vehicle emissions due to the temporary traffic management measures

Traffic control measures	**Traffic flow characteristics**		
	Fleet composition	**Speed**	**Vehicle activity**
Odd-and-even licence plate rule		√	√
Restrictions on freight trucks	√		√
Ban on yellow-labelled vehicles	√		√
Cut of government-owned vehicles		√	√

Traffic flow monitoring data indicated that total vehicle activity within the Sixth Ring Road was reduced by 32 per cent during the Summer Olympics compared with the level prior to the event, as illustrated in the comparison of GIS-gridded vehicle activity shown in figure 5.2, while after taking into account the distribution of vehicle activity, the weighted area-average speed had improved from 25 km/h to 37 km/h (figure 5.3).

The emission reduction benefits achieved during the Summer Olympics as a result of the temporary traffic management were outstanding. These results are summarized in table 5.2. Relative to the baseline scenario of June 2008, total vehicle emissions of THC, CO, NO_X and $PM_{2.5}$ decreased by 56 per cent, 57 per cent, 46 per cent and 52 per cent, respectively. In terms of daily metrics, total vehicle emissions were reduced by 206 tonnes for THC, 1,670 tonnes for CO, 129 tonnes for NO_X and 7.6 tonnes for $PM_{2.5}$ (Zhou et al., 2010).

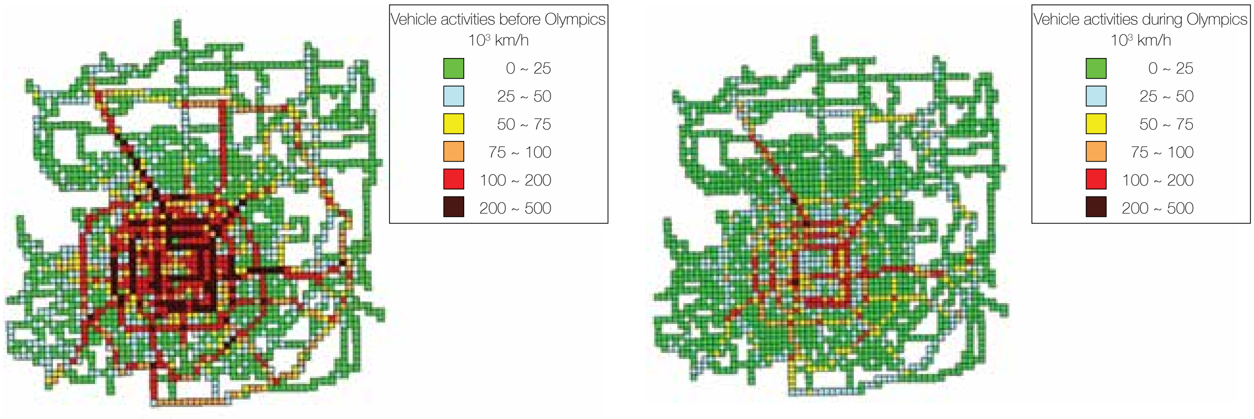


Figure 5.2 Gridded vehicle activities within the Sixth Ring Road before and during the Summer Olympics

Source: Zhou et al., 2010

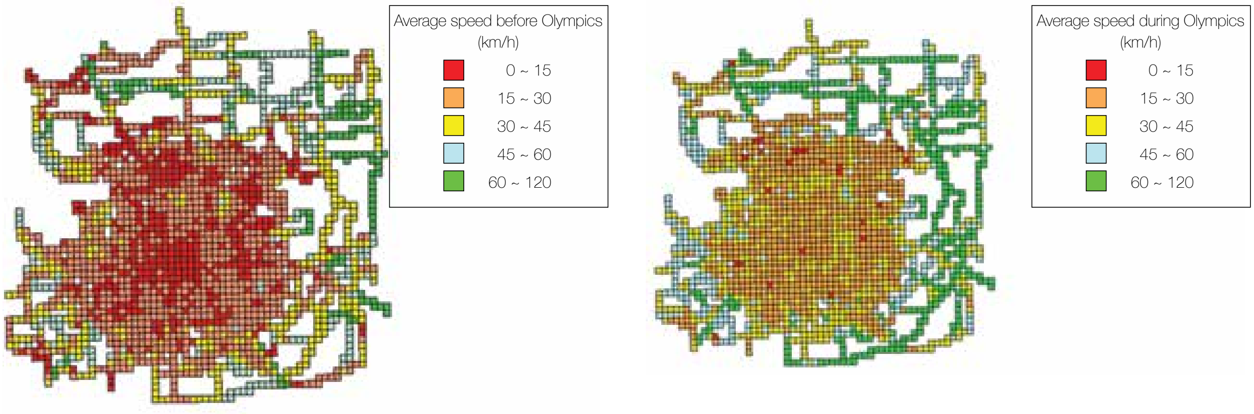


Figure 5.3 Gridded average speeds within the Sixth Ring Road before and during the Summer Olympics

Source: Zhou et al., 2010

Table 5.2 Estimated vehicle emission reductions by the temporary traffic management measures

Measures	Benefits	THC	CO	NO_x	$PM_{2.5}$
Ban on yellow-labelled vehicles	Emission reduction (tonnes)	85.9	526.5	56.8	4.9
	Reduction rate (percentage)	23	18	20	34
Odd-and-even licence plate rule	Emission reduction (tonnes)	172.7	1664.6	96.7	4.5
	Reduction rate (percentage)	47	47	34	30
Restriction of government-owned vehicles	Emission reduction (tonnes)	45.4	373.7	33.9	1.7
	Reduction rate (percentage)	12	12	12	11
Promotion of public transit	Emission reduction (tonnes)	0.8	7.5	1.5	0.2
In total	Overall daily emission reduction (tonnes)	206	1670	129	7.6
	Reduction rate (percentage)	56	57	46	52

Source: Tsinghua University, 2009

Figure 5.4 shows the changes in measured particulate matter concentrations in a traffic-populated site, the North Fourth Ring Road, and an urban background site, Miyun, during different stages related to the Summer Olympics. Substantial reductions in particulate matter concentrations were identified at both sites when traffic management measures were in effect, however, a more significant reduction was apparent at the North Fourth Ring Road site. For example, average concentrations of $PM_{2.5}$ and PM1 at the Fourth Ring Road decreased by 60 per cent and 67 per cent, respectively; in contrast, reductions of 32 per cent in $PM_{2.5}$ and 24 per cent in PM1 were recorded at the Miyun background site (Tsinghua University, 2009). Without accurately considering the short-term variations in meteorological conditions, the vehicle emission control measures during the Summer Olympics appear to have been very successful.

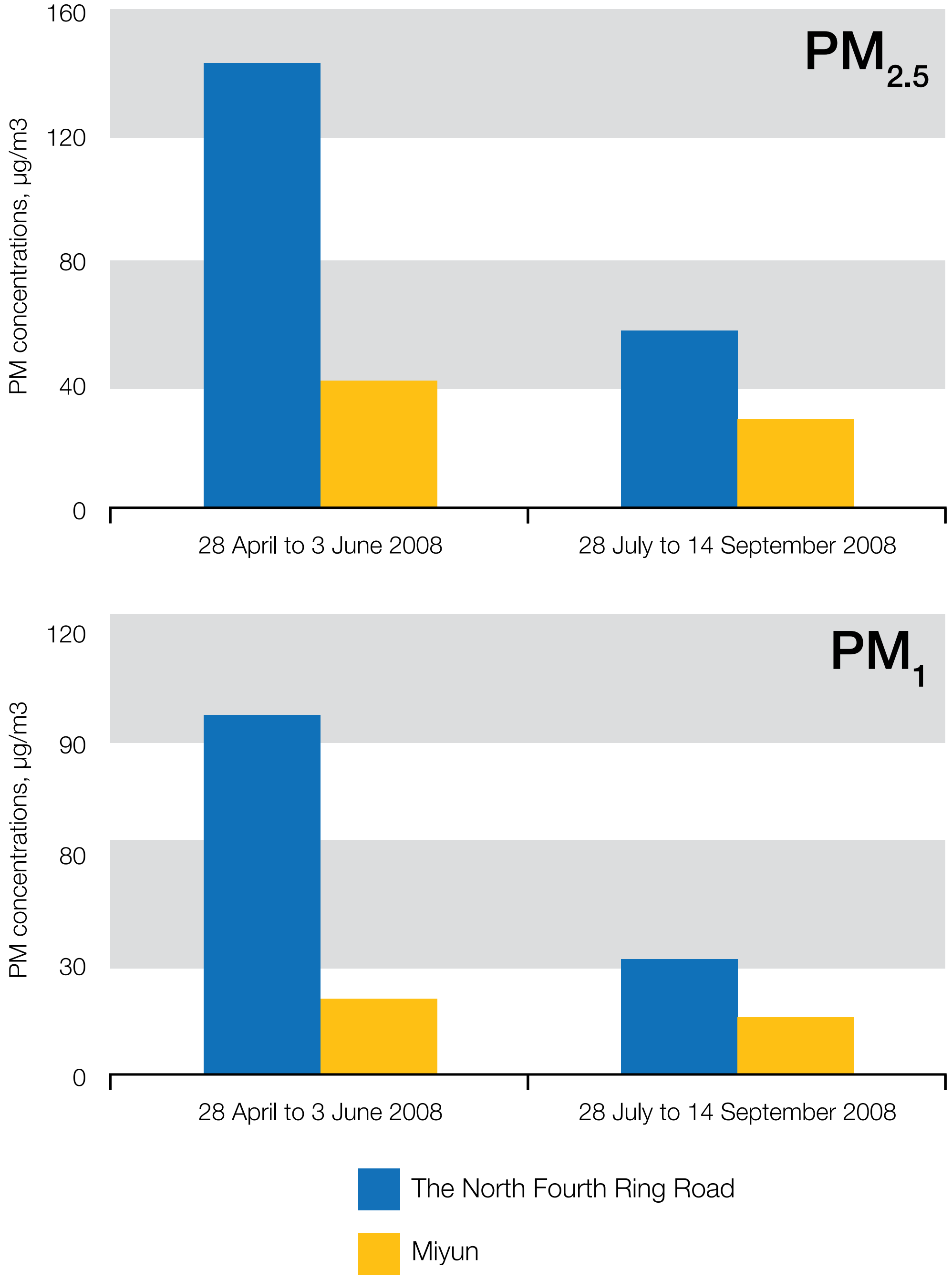


Figure 5.4 Measured concentrations of particulate matter at a traffic-populated site and an urban background site in periods of "before" and "during" the imposition of temporary traffic management measures

Source: Tsinghua University, 2009

5.2 Guaranteeing air quality for the 2014 APEC Summit

China attached great importance to guaranteeing air quality during the Asia-Pacific Economic Cooperation (APEC) Summit, which was held in Beijing from 5 to 11 November 2014. Just after the release of an action plan issued by the State Council in 2013 relevant work for assuring the air quality during the Summit started.

The air quality guarantee project was organized under the theme “two rings, two phases”. Beijing is the internal ring, and the five neighbouring provincial administrations, namely Tianjin, Hebei, Shanxi, Inner Mongolia and, Shandong, form the outer ring. “Two phases” refers to the periods before and during the Summit. In the pre-Summit phase, the primary tasks focused on advanced implementation of the Beijing Clean Air Action Plan 2013-2017, with the objective to generate environmental benefits as soon as possible. During the Summit, more targeting and stringent measures were implemented, mainly with respect to coal combustion, on-road vehicles, industrial plants and road and construction dust. By October 2014, Beijing retrofitted coal-fired boilers with a total capacity of up to 4,130 MW, scrapped more than 300,000 yellow-labelled or older vehicles and closed or restricted production at 375 polluting enterprises. To reduce road and construction dust, more than 7,000 dump trucks were renovated and construction dust pollution control measures were strengthened.

Beijing started to implement the air quality guarantee measures on 3 November 2014, two days prior to the Summit week. The temporary traffic management measures were similar to the ones adopted during the Summer Olympics. Among them were the odd-and-even licence plate rule, suspending the operations of 70 per cent of government-owned vehicles and controlling specific fleets, such as freight trucks and, dump trucks, and vehicles registered in other administrative regions.

An assessment by the government of Beijing shows that the average $PM_{2.5}$ concentration was 43 μg/m^3 during the APEC Summit. Without the effective control measures that were taken jointly by Beijing and neighbouring areas, the average $PM_{2.5}$ concentration during the event was expected to have reached 69.5 μg/m^3, an increase of 61.6 per cent. As for the total reduction of the ambient $PM_{2.5}$ concentration, such as 26.5 μg/m^3, local emission control measures were responsible for a reduction of 19.8 μg/m^3 in $PM_{2.5}$ concentration, mitigated cross-provincial transport contributed the rest, 6.8 μg/m^3. During the Summit, emissions in Beijing of SO_2, NO_X, PM_{10}, $PM_{2.5}$ and volatile organic compounds (VOCs) decreased by 39.2 per cent, 49.6 per cent, 66.6 per cent, 61.6 per cent and 33.6 per cent, respectively (Beijing Municipal Research Institute of Environmental Protection, 2014). Among the measures, temporary traffic management measures were estimated to be the most effective, amounting to 39.5 per cent of the total avoided $PM_{2.5}$ concentrations, followed by the contributions stemming from the temporary suspension of operation at construction sites and the shutdown of industrial plants or the restrictions placed on them (figure 5.5).

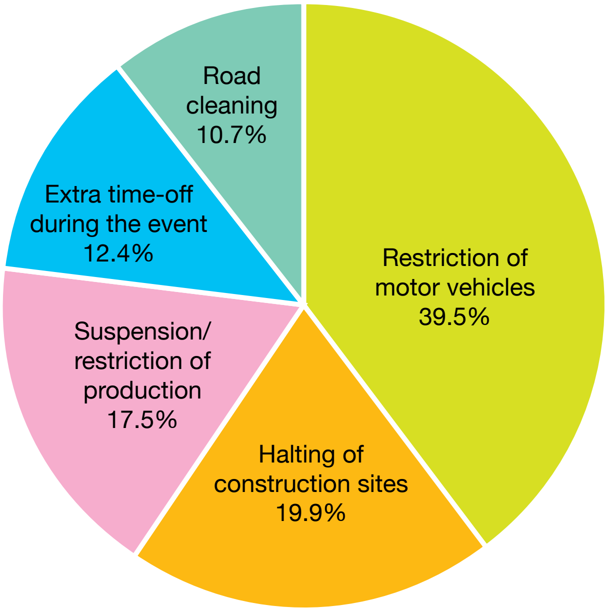


Figure 5.5 Mitigation allocation of $PM_{2.5}$ concentration among temporary control measures during the APEC Summit

Source: Beijing Municipal Research Institute of Environmental Protection, 2014

Figure 5.6 The beautiful Water Great Wall under "Beijing Blue"

Photo Credit: Beijing Municipal Publicity Center for Environmental Protection

The success achieved during the APEC Summit again reinforces the proposition that mitigating pollutant emissions substantially is the most effective approach for improving air quality. Beijing aims to sustain the success of measures implemented during the APEC Summit through various measures, including, among them, enhancing urban planning, controlling vehicle emissions, promoting clean energy, improving construction management, enlarging public participation, and establishing regional joint mechanisms for pollution prevention and control. Thus, the cheerful but short-lived "APEC Blue", which refers to the rare blue sky experienced during the Summit, will hopefully be transformed into a constant "Beijing Blue" (figure 5.6).

Chapter 6

The Experience and perspectives of Beijing

6.1 Successful experience of Beijing in air pollution control

Based on the Beijing experience, it can be said that developing a comprehensive integrated approach is key for reducing emissions of air pollutants. Without the integrated approach, the emission reduction benefits estimated in chapter 4 would not have been achieved in Beijing. Avoided emissions from the control measures have greatly contributed to a reduction in the concentration of air pollutants in the city. For example, ambient concentrations of SO_2 and CO are stable and meet both the previous and revised NAAQs. Concentration of other criteria air pollutants also declined close to levels deemed acceptable in NAAQS from 1998 to 2013. This progress has been made despite the rapid urbanization and economic development during the same period. The integrated measures included legislative, administrative, economic and technical measures to control air pollution and focused on energy structure optimization, coal-fired source control, vehicle emission control, and monitoring the progress through a systematic monitoring and reporting system.

(i) Integrated measures directed at controlling pollution from coal burning

The city's integrated approach for controlling emissions from coal burning have included the following: promotion of cleaner fuels; stringent emission standards; end-of-pipe control measures; and economic tools.

Cleaner fuel: Beijing has pursued a strategy to promote alternatives for coal, stringent emission standards and after-treatment devices. The principle ideas of promoting alternatives for coal have included mitigating coal use by importing electricity, increasing natural gas and using renewable energy. Natural gas has played a fundamental role in reducing coal consumption. The city has established multiple gas sources and transport channels to guarantee the gas supply and considered LNG and coal-based synthetic gas as future sources. With regard to imported electricity, Beijing has taken advantage of the existing power capacity in neighbouring energy-producing provinces, primarily Shanxi and the western part of Inner Mongolia, and enhanced the capacity of electricity interconnection, transmission and distribution with the objective to increase the ratio of imported electricity. Over the past 15 years, the share of clean energy in total energy consumption has increased from below 20 per cent to close to 50 per cent (Beijing Municipal Statistics Bureau, 2014), which has supported the establishment of a solid foundation for replacing coal consumption in Beijing.

Stringent emission standards: Strict emission standards are essential for emission control from coal use. The emission limits of major air pollutants for coal-fired boilers have been tightened twice, in 2002 and in 2007. Beijing has introduced one of the most stringent emission standards for newly built coal-fired power plants in the world. Specifically, the limits of PM and SO_2 were revised to 10 mg/m^3 and 20 mg/m^3 in 2007, or tightened by 80 per cent and 95 per cent, respectively, relative to the limits set in 1998. Meanwhile, the NO_X limit was set at 100 mg/m^3; there was no specific NO_X emission limit in 1998. The most recent emission standard for coal-fired boilers was first introduced in Beijing and then later was part of the national standard amendment that was issued in 2012. This standard has effectively promoted clean, efficient and concentrated use of coal in China.

End-of-pipe control measures: Beijing has implemented end-of-pipe control measures on various coal-fired sources. These measures have primarily concentrated on power plants, industrial boilers and residential heating sectors. Major efforts are focused on retrofitting by adding pipe-end control devices, such as flue gas dust-removal, desulfurization and denitration, and promoting natural gas and electricity as replacements for coal-fired boilers and residential heating in old house areas. Those actions have substantially reduced coal-fired emissions of major air pollutants. Taking the coal-fired power plants as an example, relative to the w/o control scenario, advanced after-treatment devices strictly supervised by the continuous emission measurement system could reduce emissions of PM_{10}, $PM_{2.5}$ and SO_2 by more than 80 per cent and those of NO_X by approximately 70 per cent.

Economic tools: Economic incentives are an important driving force to improve emission mitigation in Beijing. During 2002, 2005, 2010 and 2014, the Beijing Municipal Environmental Protection Bureau and the Finance Bureau jointly released a series of documents to provide subsidies for retrofitting coal-fired boilers. The subsidized items included replacement of coal-fired boilers by natural gas, electricity or by connecting with district heating system as well as retrofit programmes for using low nitrogen combustion devices. Furthermore, lower electricity price during off-peak hours and additional subsidies from governments guarantee that the average electricity cost after renovating a heating system in old house areas is comparable and even lower than previously used coal-burning heating system. Effective economic incentives have become a powerful lever for making continuous progress in coal-fired emission control stage by stage.

(ii) Vehicle emission control

The vehicle-fuel-road integrated control framework, which was developed to suit local conditions, focused on tightening emission standards for new vehicles, fuel quality improvement, law enforcement and promoting sustainable transportation. The city's experience has been largely followed by other Chinese cities and has served as a valuable reference for improving the vehicle emission management system at the national level.

Continuing to tighten emission standards on new vehicles: This report indicates that increasing stringent emission standards regularly has been the most effective pollution control measure adopted in Beijing. To guarantee the effectiveness of stringent emission standards, there is need to strictly supervise the type-approval conformity over the market sales. For example, PEMS has been used to ensure the type-approval conformity.

Synchronizing fuel quality with emission standards: A mismatch between fuel quality and vehicle emission standards should be avoided. Recognizing this, Beijing has improved fuel quality, such as low sulfur content, simultaneously with the implementation of stringent vehicle emission standards. By improving fuel quality, significant benefits can be generated from tightened emission standards. Over the period 1998-2013, Beijing made unleaded gasoline available throughout the city and continuously reduced sulfur contents of on-road fuels, such as the ultra-low sulfur gasoline and diesel fuels, complying with the China 5/V standards. The sulfur contents of gasoline and diesel fuels are both 10 ppm, making it possible to use advanced after-treatment devices. It should also be noted that Beijing has promoted fuel diversity among public fleets, including public transit buses and sanitation and postal vehicles, and is promoting the addition of natural gas vehicles, electric vehicles and hybrid vehicles to the public fleets.

Effective supervision and law enforcement on in-use vehicles: Beijing has combined regular in-use inspection programmes and enhanced on-road monitoring methods by deploying, for example, remote sensing to improve the efficiency of in-use vehicle controls. With increased capacity to enforce regulations, Beijing is taking full advantage of public supervision to enhance in-use vehicle emission control. For example, the city introduced an environmental labelling system for managing high emitters. The yellow-labelled vehicles representing high-emitters has been restricted in urban areas and subsidized to accelerate their scrappage. Beijing has created this mechanism with the intention to phase out older vehicles, largely relying on economic incentives, to effectively increase the fleet turnover rate.

Promoting sustainable transportation: Transportation planning and traffic management are playing an increasingly important role in alleviating the rapid increase of vehicle stock and high vehicle-use intensity. Beijing has emphasized the importance of advanced transportation planning and traffic management in vehicle emission control. During the period 1998-2013, the city strived to develop the public transport system, using a rail-based networking as its backbone. For public buses, bus lanes and BRT routes have been established to improve the service level. In addition, Beijing has adopted strict restrictions on car driving during weekdays and the licence control policy, which have effectively eased traffic congestion and increased the share of travel by public transport.

(iii) Air quality monitoring and reporting system

Monitoring and reporting is part of air pollution control measures. It helps to identify the sources of pollution and to design appropriate control measures for those sources. A $PM_{2.5}$ source apportionment study conducted in Beijing identified the $PM_{2.5}$ sources and supported the development of a strategy for controlling $PM_{2.5}$. In addition, monitoring can also be useful for evaluating the effectiveness of air pollution control measures implemented in Beijing. Most importantly, an air quality monitoring system can inform authorities about the progress in achieving air quality targets.

For many cities, educating senior decision makers and the public should be the very first step towards developing and implementing an air pollution control action plan and building an air quality monitoring system. In addition, releasing air quality information on a regular basis to the public could be an effective way to raise awareness about the need for air pollution actions. Key aspects in maintaining a reliable monitoring and reporting system are updating the system to meet the needs of the NAAQs and ensuring quality assistance/quality control (QA/QC).

Upgrading air quality monitoring network: Beijing established its first generation air quality monitoring network in 1982 when China released its first NAAQS. The air quality monitoring network has been expanded in line with amendments to NAAQS. The latest NAAQS revision was issued in 2012 and Beijing accordingly enhanced its air quality monitoring network. Currently, 35 substations, which are spatially distributed in the 16 administrative districts/counties, and an economic-technological development zone cover four major categories of a monitoring function needed to evaluate urban air quality, background air quality and the interprovincial transport contribution. In particular, the substations are capable of measuring ambient $PM_{2.5}$ concentration.

Enhancing quality assurance and quality control: Beijing has established a laboratory for the environmental monitoring system with necessary facilities and improved the quality system documents and reference standard samples to enhance QA/QC. The quality management system has been improved to make the QC more systematic, standardized and effective. The staff periodically inspects and maintains the monitoring system according to the standards and regulations, covering sampling systems, analytic instruments, data collection and transmission, and calibration facilities. The inspection and maintenance records are retained and traceable to investigate causes for possible abnormal cases and take remedial actions as appropriate. The capacity of the staff has been enhanced through training and exchange programmes. All the staff members are responsible for the automatic monitoring have been strictly assessed and are certified.

6.2 Future air pollution control in Beijing: prospects and reflections

In 2013, Beijing started to enforce the new NAAQs and initiated a major effort to control $PM_{2.5}$ pollution. According to NAAQs, the annual $PM_{2.5}$ concentration needs to be below 35 μg/m^3 by 2030. There is no easy shortcut to achieve this. It will involve working hard over the next fifteen years. As the first step in this endeavour, Beijing issued the Clean Air Action Plan 2013-2017 in 2013, which is serving as the first Five-Year Plan for $PM_{2.5}$ pollution control. The overall objective of this plan is to significantly improve air quality in Beijing, substantially reduce the number of heavy pollution days, and mitigate the annual concentration of $PM_{2.5}$ by approximately 25 per cent in 2017 relative to the level in 2012. To achieve this goal, the plan contains specific and intensive control measures covering energy structure optimization, vehicle emission control, industrial structure upgrading, enhancement of pipe-end treatment, fine-grained urban management, ecological environmental improvement, and emergency response during heavy pollution episodes. From a long-term perspective, Beijing should make extensive efforts in the following fields to improve air quality.

(1) Accelerate and improve the construction of a legal institution regarding air pollution control

Enforcement of the Environmental Protection Law and the Law on the Prevention and Control of Atmospheric Pollution. Air pollution control relies not only on advanced technology, but also on effective governance, including a sound legal system, full law enforcement and strict supervision. At the national level, the Environmental Protection Law of China, was amended in 2014. It approved the principle of joint prevention and control of regional air pollution and is regarded as the most stringent environmental protection law in the country. On the other hand, the revision of the Law on the Prevention and Control of Atmospheric Pollution was completed in 2015.

Continuing to improve and deepen the Regulations of Beijing Municipality on the Prevention and Control of Atmospheric Pollution. In 2008, Beijing began to revise the Regulations of Beijing Municipality on the Prevention and Control of Atmospheric Pollution. The amendment was officially enacted in January 2014. The revised regulations better defines the relationship between economic development and environmental protection, and strengthens air pollution controls placed on on-road vehicles, VOC sources and non-road mobile sources, and dust and backs them up with powerful legal support.

(2) Improving the city planning, optimizing the layout of city functions and promoting the development plan for Beijing, Tianjin and Hebei

Improving city planning and optimizing the layout of city functions. The urban space and population size of Beijing have increased rapidly over the past 15 years, resulting in enormous environmental and development pressure. Beijing must thoroughly understand the environmental and urban growth objectives early on, including a timely upgrading of its industrial structure, in order to avoid excessive expansion of the urban area and population. The city intends to implement an urban master planning and primary function area development strategy, categorize regions and industrial sectors, control construction intensity to a reasonable level, improve the layout of city functions and form a favourable space layout for pollutant dispersion.

Implementing a regional cooperative development plan for Beijing, Tianjin and Hebei. The success related to controlling air quality during the 2008 Summer Olympics and the 2014 APEC Summit highlighted the importance of regional cooperation for air pollution control. With that in mind, the Political Bureau of the Communist Party of the Central Committee approved in April 2015 an outline plan for coordinated development of Beijing, Tianjin and Hebei, which explicitly clarifies that non-core functions in the capital should be weakened and transferred into neighbouring areas, such as Hebei and Tianjin. Transportation integration, environmental protection and industrial upgrading are the key areas in the plan. Beijing will re-evaluate and clarify its functions and urban development planning programme, promote industrial development, control the intensity of development, limit urban energy consumption, and modify the urban layout in favour of atmospheric pollutant dispersion. It should be noted that cross-boundary transport is a major factor behind the high $PM_{2.5}$ concentration of Beijing. The source apportionment results indicate that during some particularly heavy pollution episodes, cross-boundary transport's contribution to the high $PM_{2.5}$ contribution has exceeded 50 per cent. The regional collaborative development plan will further promote joint control of atmospheric pollution, technically improve the capabilities of ambient air quality monitoring and forecasting, provide significant pollution warning and supervise key emission sources, such as residential coal use in the rural areas, non-road mobile source and agricultural ammonia emissions, in neighbouring provinces.

(3) Constantly promoting clean energy and in-depth control of coal-fired emissions

Strengthening the sustainable supply of clean energy. The Clean Air Action Plan 2013-2017 clearly proposes to limit total coal consumption in Beijing to no more than 10 million tonnes by 2017. Beijing has set a goal to make natural gas the dominant energy form of municipal electricity production, and import up to 70 per cent of total electricity demand from other regions. As a result, electricity is expected to account for 40 per cent of total final energy consumption in Beijing by 2017. Beijing also plans to establish an annual supply capability of 24 bcm through diversified gas sources and multichannel transportation methods, such as pipeline gas, coal-based synthetic gas and liquefied gas.

Full penetration of natural gas to local power units and enhancement of end-pipe emission control. Beijing plans to replace its four major coal-fired power plants with natural gas turbines within two or three years; four thermal-power cogeneration centres will be completed by 2016. Total emissions from local electricity production are expected to further decrease in the near future. It should be noted that the city's local power and industrial energy will rely considerably on gas-fired turbines in the future. Due to the NO_X formation mechanisms, emphasis should be placed on the online measurement system of NO_X emissions for gas turbines, and if necessary, NO_X emission limits for gas turbines should be tightened to encourage the application of SCRs and other denitrification after-treatment devices.

Phasing out coal consumption in the urban districts and reducing coal consumption in the rural districts and counties. In terms of coal-fired boilers, direct coal consumption in the core districts of Beijing was ended by 2015. Most of the coal-fired coal boilers in six urban districts with a capacity of 35 GW, which are mainly located in Chaoyang, Haidian, Fengtai and Shijingshan districts, were planned to be converted to natural gas by 2015. For remote rural districts and counties, total coal consumption for each prefecture -level region is required to be mitigated by 20 to 35 per cent. Coal-boilers with capacity lower than 7 MW are to be completely phased out and the existing concentrated heating supply centres and to be gradually subsidized to entice them to use clean energy, such as natural gas. Economic incentives can continue to play an effective role in promoting the energy structure shift in the future.

Given that the supply of natural gas is still relatively tight and unstable in many other cities, the strategy to switch from coal to gas should be optimized based on cost-effectiveness and distributional impacts. This can be determined by conducting a comparison of various regions and emission sources, such as coal-fired power plants and industrial boilers, domestic heating and diesel-fueled commercial vehicles and machinery.

(4) Further development of the public transit system and improvement of the "vehicle-fuel-road" integrated emission control system.

Further develop green transportation, including public transit and slow traffic modes. Beijing will further develop its green transportation network, optimize the operation, upgrade the comfort levels, and improve the management of rail-based and ground public transit systems. In particular, rail-based transportation will play an increasingly important role in intracity and intercity trips. The conditions for slow traffic will be improved by increasing the number of bike and pedestrian lanes. The total length of rail-based transportation lines will increase to 660 km. By 2017, the share of using of public transit, such as buses and subways, in the urban area out of all travel modes (see figure 3.6, not including walking) is aimed to reach 52 per cent, and account for more than 60 per cent of total motorized trips.

Continue to implement more stringent standards for vehicle emissions and fuel quality. Beijing will fully implement the China V emission standard for all heavy-duty diesel vehicles, and those operating in the city range will be required to add DPFs. The more strict China 6/VI emission standards will be implemented not later than 2017. The applicable fuels for the China 6/VI emission standards will simultaneously be required.
As a traffic-dense metropolitan city, Beijing is facing tremendous pressure stemming from the rapid increase in vehicle stock and temporally and spatially concentrated vehicle activity. It has no other solution but to learn from more international experiences and constantly tighten vehicle emission standards. For example, Beijing should consider more strict emission standards than those set in the Euro 6/VI, and target ones similar to the LEV III standards for light-duty vehicles adopted by California in the United States. Beijing will also continue to improve fuel quality by tightening standards and strengthening market supervision. Among the issues it needs to address include lowering gasoline volatility, improving fuel detergency, controlling toxic fuel compounds and unifying standard systems for on-road and non-road diesel engines.

Accelerating the scrappage of older vehicles and enhancing the inspection and control of in-use vehicles. Beijing will further enhance emission control oversight for in-use vehicles by using the advanced remote-sensing method and conducting inspections at vehicle-owner companies, such as bus companies and commercial transportation firms. In particular, on-road diesel trucks and dump trucks will be two major targeted fleets for in-use inspection. Along with the advanced on-road inspection system, economic incentives will continue to be applied in Beijing to spur the scrappage of yellow-labelled and older vehicles. Existing yellow-labelled vehicles in Beijing were planned to be completely scrapped by 2015 and more than one million older vehicles are targeted to be phased out by 2017. Beijing should cooperate closely with the surrounding provinces on a regional joint platform to control high-emitting diesel freight trucks registered in the regions outside Beijing.

Furthermore, durable vehicle emission controls over the lifetime of the vehicle complement stringent emission standards to improve air quality. The experiences from the United States clearly indicate that a recall mechanism for comprehensive and routine in-use compliance testing is fundamental to identifying non-compliance and assure durable emission controls. An improved legal system for vehicle emission control that includes regulations requiring manufacturers to report to the government emission-related defects in their products is needed This would help guide recall testing and prods manufacturers to repair and re-establish the durability of emission controls. Such a system also can provide a platform for off-cycle testing to seek out defeat devices.

Promotion of new energy vehicles and clean transportation fuels. Beijing will further promote new energy vehicles, such as battery electric vehicles and plug-in hybrid electric vehicles, and clean transportation fuels, such as natural gas, and construct auxiliary infrastructure, such as charging lots, charging stations and gas filling stations. As a result, the transportation fuel structure of public transit buses, taxis, sanitation and postal vehicles will be more diverse and environmentally friendly. With regard to emerging technologies, their real-world and life-cycle emissions will be carefully assessed. For example, it should be noted that the lean-burn gas combustion technology is more prevalent in natural gas bus fleets of China, which will lead to high real-world NO_X emissions. Therefore, stoichiometric engines and advanced after-treatment devices, such as three-way catalysts and SCRs, should be developed for natural gas vehicles.

Developing traffic infrastructure and an intelligent traffic system, and improving traffic management. Beijing is focusing on advanced traffic management in vehicle emission control. The city plans to continue to implement its licence control policy to limit total vehicle population, enhance parking management and improve driving restrictions on cars according to areas and hours. For trucks registered in other provincial regions, it will build more bypass highways to reduce the adverse impact on urban air quality from them. In addition, Internet-of-Things and big data-supported traffic intelligent systems and vehicle emission control decision-making platforms will be developed, which will improve the city management and play a more important role in reducing vehicle-use intensity and emissions of air pollutants.

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