

On-Road Vehicle Emission Control in Beijing: Past, Present, and Future[†]

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Beijing, the capital of China, has experienced rapid motorization since 1990; a trend that is likely to continue. The growth in vehicles and the corresponding emissions create challenges to improving the urban air quality. In an effort to reduce the impact of vehicle emissions on urban air quality, Beijing has adopted a number of vehicle emission control strategies and policies since the mid 1990s. These are classified into seven categories: (1) emission control on new vehicles; (2) emission control on in-use vehicles; (3) fuel quality improvements; (4) alternative-fuel and advanced vehicles; (5) economic policies; (6) public transport; and (7) temporal traffic control measures. Many have proven to be successful, such as the Euro emission standards, unleaded gasoline and low sulfur fuel, temporal traffic control measures during the Beijing Olympic Games, etc. Some, however, have been failures, such as the gasoline-to-LPG taxi retrofit program. Thanks to the emission standards for new vehicles as well as other controls, the fleet-average emission rates of CO, HC, NO_x, and PM₁₀ by each major vehicle category are decreasing over time. For example, gasoline cars decreased fleet-average emission factors by 12.5% for CO, 10.0% for HC, 5.8% for NO_x, and 13.0% for PM₁₀ annually since 1995, and such a trend is likely to continue. Total emissions for Beijing's vehicle fleet increased from 1995 to 1998. However, they show a clear and steady decrease between 1999 and 2009. In 2009, total emissions of CO, HC, NO_x, and PM₁₀ were 845 000 t, 121 000 t, 84 000 t, and 3700 t, respectively; with reductions of 47%, 49%, 47%, and 42%, relative to 1998. Beijing has been considered a pioneer in controlling vehicle emissions within China, similar to the role of California to the U.S. The continued rapid growth of vehicles, however, is challenging Beijing's policy-makers.

Introduction

China's three decades of economic growth have lifted millions out of poverty and is considered an economic miracle. Rapid urbanization—the urban population was as low as 20% of total population in 1980, increasing to 38% by the end of 2002 and 47% by the end of 2009 (1)—often creates a desire for greater mobility. Beijing, the capital of China, demonstrates this association quite well. It took 48 years, from 1949 to 1997, for Beijing to reach one million on-road vehicles and only two years, from 2007 to 2009 to grow from three

million to four million. Figure 1 illustrates the growth of on-road vehicles in Beijing over the past two decades, with an annual growth rate as high as 13%. By end of 2009, Beijing's total vehicle population reached 4.02 million (2).

The rapid growth in motor vehicles creates air quality challenges. Researchers have identified mobile sources as one of the most important contributors to Beijing's air pollution (3–8). For example, Hao et al. (4) report that in 1995 emissions from vehicles contributed 76.5% and 68.4% of total CO and NO_x concentrations, respectively, in Greater Beijing and 86.3% and 72.0%, respectively, in downtown Beijing. Westerdahl et al (7) found road traffic to be a major cause of ultrafine particles in Beijing. For the summer ozone problem, on-road vehicles are the leading contributors as the leading sources of ozone precursors—VOCs and NO_x (8). Many studies have confirmed that urban air pollution in Beijing has shifted from being dominated by coal burning to a mix of coal burning and vehicle emissions.

In order to reduce the impact of vehicle emissions on urban air quality, Beijing has adopted many vehicle emission control strategies and policies since mid 1990s. These strategies and policies include adopting a series of European emission standards for new light-duty vehicles (LDV) and new heavy-duty vehicles (HDV), enhancing the annual inspection and maintenance (I/M) program, improving fuel quality, scrapping high-emitting vehicles, and more. In addition, many temporary transportation control measures were implemented during the summer of 2008 for the 2008 Olympic Games. As a result, a significant reduction in vehicle emissions as well as improvement of overall air quality was achieved during the period (8, 9). Beijing is considered a pioneer in controlling vehicle emissions in China, similar to the role California plays in the U.S.

In this paper, we summarize the vehicle control strategies and policies in Beijing since the mid 1990s. We discuss the background and content of major strategies, evaluate the emission profiles of Beijing's vehicle fleet between 1995 and 2009 and assess the emission reductions of each major strategy. This paper aims to help policy-makers understand the past and current vehicle control strategies and their effects on emissions and air quality. We also discuss potential future strategies for Beijing's vehicle fleet and explore long-term mechanisms for vehicle emission control in Beijing and the rest of China.

Vehicle Emission Control Strategies and Policies

The control strategies and policies for Beijing's vehicle fleet over the past two decades can generally be classified into seven categories. The first six are standard controls programs,

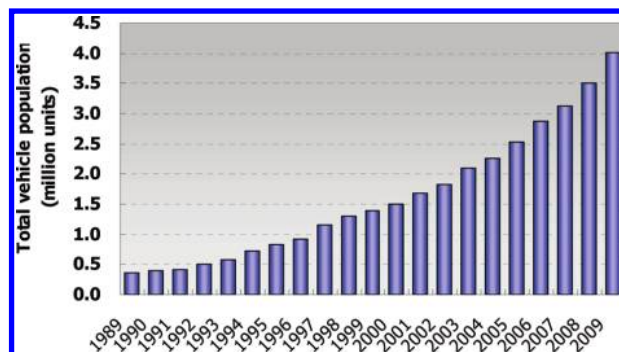


FIGURE 1. Growth in total vehicle population in Beijing, 1989–2009.

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including (1) controls on new vehicles; (2) controls on in-use vehicles; (3) improvements in fuel quality; (4) alternative fuel vehicles and advanced vehicles; (5) economic policies including fiscal incentives and vehicle emission taxes/fees; and (6) public transportation. The seventh category is temporal controls, in particular, traffic control measures implemented during and after the Beijing Olympic Games.

1. Control of New Vehicles. The first emission standards for on-road vehicles in China were issued in 1992. The standards were a series of driving cycle emission regulations for both light- and heavy-duty vehicles (5). For light-duty vehicles, the limits are equivalent to the ECE (Economic Commission for Europe) R15-03 standard. The emission rates for heavy-duty engines are those of the U.S. in the late 1970s. Motorcycles were also subject to an emission standard equivalent to that enforced in Europe in the 1980s. However, these emission regulations did not put pressure on manufacturers because most new vehicles could meet those standards without significant upgrades.

In 1994, the State Environmental Protection Administration (SEPA) initiated a comprehensive study at the national level, namely “China’s Strategies for Controlling Motor Vehicle Emissions”. This project carried out extensive laboratory tests for 62 cars, 44 minivans and light-duty trucks, 13 heavy-duty engines, and 52 motorcycles using a chassis dynamometer. After analyzing test results, the research team strongly recommended more stringent emission standards (such as Euro 1) targeted at new vehicles along with other control measures. Without such measures, the team suggested it would be impossible to mitigate emissions from on-road vehicles in big cities, such as Beijing and Guangzhou. Consequently, urban air quality would deteriorate (10). As a result of the study and recommendations, SEPA promoted new regulations for new vehicles. This new regulation required Euro 1 and Euro 2 emission standards in 2000 and 2004, respectively, nationwide (11).

In 1997, Beijing launched a program, namely “Strategies and Implementation Plan for Controlling Motor Vehicle Emissions in Beijing”. The goal was to set up a step-by-step implementation plan (IP) of Euro emission standards for Beijing. At that time, a dramatic increase in new light-duty vehicles in Beijing was underway—the annual average growth rate of the passenger car fleet between 1995 and 1998 was as high as ~45%. Consequently, annual CO and NO_x concentrations near some major roads were observed to increase by ~20–30% and ~40–80%, respectively, from 1991 to 1998 (12). To offset the increasing emissions from the rapid growth of the vehicle population, Beijing implemented the Euro emission standards on an accelerated timeline. On January 1, 1999, Beijing Environmental Protection Bureau (EPB) tightened the vehicle emission standards, that is, Euro 1 for light-duty vehicles, and required that new gasoline cars be equipped with electronic fuel injection (EFI) and three-way catalysts (TWC) (13). It was one year earlier than required by the national emission standards. This first-ever emission standard implemented in Beijing resulted in a dramatic decrease in emission factors of new vehicles relative to the carburetor counterparts (the so-called Euro 0 models). As illustrated in Supporting Information (SI) Table S1, the limits from the pre-Euro 1 to Euro 1 provided the greatest reductions in terms of absolute values; more than the change from Euro 1 to Euro 2, or Euro 3 to Euro 4.

Table 1 summarizes the vehicle emission standards adopted in Beijing since 1999. Generally, the Beijing EPB tightens the emission standards for new vehicles every 3–4 years. For light-duty gasoline vehicles and trucks (LDGV and LDGT) and heavy-duty diesel vehicles (HDDV) the standards are at least one year earlier than the national requirements. To strengthen the control of new LDGV is primarily due to the high growth rate of this vehicle category. As shown in SI

TABLE 1. Summary of Emission Standards for New Vehicles Adopted in Beijing, 1999–2009

| | Euro 1 | Euro 2 | Euro 3 | Euro 4 |
|-------------------|----------|----------|------------|-----------------------|
| LDGV ^a | 1999-1-1 | 2003-1-1 | 2005-12-30 | 2008-3-1 |
| HDGV ^b | 2002-7-1 | 2003-9-1 | 2009-7-1 | |
| HDDV ^c | 2000-1-1 | 2003-1-1 | 2005-12-30 | 2008-7-1 ^e |
| MC ^d | 2001-1-1 | 2004-1-1 | 2008-7-1 | |

^a Light-duty gasoline vehicle. ^b Heavy-duty gasoline vehicle. ^c Heavy-duty diesel vehicle. ^d Motorcycle. ^e Only for public fleets including buses, postal and sanitation vehicles.

Figure S1, LDGV (i.e., passenger cars in this study) has been increasing its share of total vehicle fleet significantly since 1995, from 16.6% in 1995, to 35.5% in 2000, 52.4% in 2005, and 62.8% in 2009. Although HDDV accounts a relatively small share of total vehicle population in Beijing (SI Figure S1), this vehicle category contributes substantial emissions of NO_x and PM_{2.5} (9, 12, 14). This is a major reason that Beijing EPB promotes the control of HDDV as hard as that of LDGV. Table 1 illustrates the rapid change in Beijing’s vehicle emission standards. Before 1999, vehicles sold in Beijing were primarily carburetor vehicles without after-treatment control, technology ~15–20 years behind European countries. When Beijing phased in Euro 1 in 1999, the gap between Beijing and Europe was less than 10 years; with the implementation of Euro 4 in 2008, the gap is only three years.

More stringent emission regulations for new vehicles have been the most important control measures to mitigate fleet-average emission factors in Beijing. The next section presents a detailed discussion of this issue. Hao et al. (12) report that implementing Euro 1/2 in the early 2000s was the most cost-effective way to reduce vehicle emissions in Beijing compared to other control measures for in-use vehicles (such as retrofit and scrapping programs). SI Table S2 summarizes available control technologies (ACT) for each emission standard for major vehicle categories. SEPA issued guidelines for control technologies for new vehicles in June 1999. The details are documented in Hao et al. (12).

Recently, Beijing EPB began promoting regulations for new emission standards, i.e., Euro 5 in ~2012 and Euro 6 in ~2016. It should be noted that Euro 5 and Euro 6 emission standards focus primarily on controls in HDDV. For LDGV, the limit values are only tightened for NO_x.

2. Control of In-Use Vehicles. Although the emission regulations to control new vehicles discussed above are directly toward limiting or decreasing emissions from in-use vehicles ultimately, the Beijing government also implemented specific measures to control in-use emissions. The I/M program was one of the most effective means for reducing emissions of in-use vehicles (15). However, there is also an argument that an I/M program without quality assurance and effective supervisory systems wastes money and time. Beijing EPB issued the first-ever two-speed idle test protocol at a city-level in China in 1994 (16). In 1995, Beijing started a pilot I/M study to evaluate the impacts of two-speed idle tests. The results indicated that CO and HC emissions from in-use vehicles could be significantly reduced by good maintenance after the identification of high emitting vehicles (12). For example, after maintenance the concentrations of CO were reduced by 61% in average at idle and 39% at high speed idle (~2000 rpm) for 2452 tested vehicles (SI Figure S2). Accordingly, with the new test data Beijing EPB revised the cut points of the two-speed idle test protocol for gasoline vehicles, beginning in 1999 (16).

However, with this I/M demonstration, the two-speed idle test procedure did not provide accurate, real-world NO_x

emission data for vehicles. Instead, the Acceleration Simulation Mode (ASM) test was considered to more closely represent real-world conditions (especially for NO_x) than the two-speed idle test. To strengthen NO_x emission control, Beijing EPB started to implement an enhanced I/M program with the ASM test protocol in 2001 (17). By end of 2004, ~200 ASM test lanes were in operation in Beijing. Comparing the ASM test protocols implemented in Beijing and the U.S. (17, 18), the cut points for light-duty vehicles with similar control levels were more stringent in Beijing than in the U.S. For example, the vehicles with model-year between 1999 and 2002 in Beijing are typically Euro 1 vehicles, which are similar in control to those vehicles with model-year in the 1980s in the U.S. As shown in SI Figure S3, the cut points for vehicle-model-year after 1999 in Beijing are 75 ppm for HC, 0.5% for CO and 700 ppm for NO_x ; whereas in the U.S., the cut points for vehicles with model-year in the 1980s are much higher, 150 ppm for HC, 1.0% for CO, and 1000 ppm for NO_x . As a result, the number of light-duty vehicles that failed the ASM test increased significantly, for example, a failure rate of more than 30% during the first month of required ASM testing was reported by Beijing EPB. Not surprisingly, the high failure rate triggered concerns that vehicle owners would seek shortcuts to pass the emission tests, reducing the effectiveness of the I/M program. Beijing EPB has tightened the supervision of the I/M program to fight potential fraud.

Retrofits of some vehicles were considered another useful approach to reduce emissions, especially in a short time period. However, the retrofit program was subject to a debate on the legality and long-term cost-effectiveness. Beijing EPB initiated a large retrofit program for light-duty vehicles in 1999. As many as 190 000 carbureted vehicles registered after 1995 were retrofitted with a three-way catalyst, supplemented with air and closed-loop controls by the end of 2001. The follow-up test and evaluation program indicated that CO emissions were reduced by 78–90% while HC + NO_x emissions were lowered by 71–88% immediately after the retrofit (19). It should be noted that most of these retrofitted emission control systems, however, were only durable for a relatively short period (e.g., a guarantee by the manufacturer for 2 years). It is believed that most of these retrofitted vehicles deteriorated more significantly than their Euro 1 counterparts, and they become high emitting vehicles after a couple of years. Another major retrofit program was to convert gasoline taxis to flexible-fueled vehicles (FFV) with either gasoline or liquefied-petroleum gas (LPG). This will be described in more detail below. This retrofit program was eventually considered to be a failure.

An environmental labeling policy for in-use vehicles was implemented in Beijing beginning in 1998. The program is a real success story. According to this policy, each vehicle registered in Beijing is issued a label either in yellow or green, indicating the emission standard of the vehicle. The label must be affixed to the vehicle's front window. For example, pre-Euro 1 LDGV are issued a yellow label and Euro 1–4 LDGV are issued a green label with stars indicating the standard (e.g., Euro 3 is with a three-star green label). Such a system enables specific controls or restrictions on yellow-labeled vehicles (also known as high-emitting vehicles). The most well-known control is restrictions on driving in Beijing. Starting in 2003, the yellow-labeled vehicles were not allowed to drive within the downtown area (within the Second-Ring Road, ~60 km²) of Beijing. The restriction area has subsequently expanded to the Sixth-Ring Road (~2000 km²).

Driving restrictions also target some vehicle categories. Motorcycles (MC) have been banned within the Fourth-Ring Road since 2001, resulting in a significant decrease in total MC population and annual distance traveled. In 2001 the total MC population was around 344 thousand units, now the number is 193 thousand units. Heavy-duty trucks are

not allowed within the Fourth-Ring Road during the daytime (6:00–23:00). This inevitably affects the diurnal NO_x and $\text{PM}_{2.5}$ emission profiles from vehicles in Beijing.

Scrapping older, high-emitting in-use vehicles is usually considered another effective way to reduce vehicle emissions. For example, a pre-Euro 1 carburetor car emits 41, 31, 19, and 9 times more HC, CO, NO_x , and $\text{PM}_{2.5}$, respectively, than a Euro 4 car (2). Beijing EPB has been promoting several major scrap programs since 1999, again focused on yellow-labeled vehicles. In 1998–1999, more than 20 000 yellow-labeled min-van cabs were phased out. Since late 2000, to purchase a new Euro 1 or Euro 2 heavy-duty diesel trucks, the owners have to phase out at least one pre-Euro 1 truck. Since 2005, more than 7000 heavy-duty gasoline buses have been scrapped, most of which were Euro 0 and Euro 1 engines. Beijing also requires mandatory retirement of taxis within 8 years of their model year due to high annual mileage. To create more support and provide stronger incentives, the scrap programs often include a fiscal incentive. For example, more than 100 000 yellow-labeled vehicles were successfully phased out in Beijing in 2009, largely thanks to a large subsidy to the owners of the scrapped vehicles.

3. Improvements in Fuel Quality. A close relationship between fuel quality and vehicle emissions has been confirmed by several studies (5, 12, 19, 20). Major indicators of gasoline quality include octane, Reid vapor pressure (RVP), lead content, sulfur content, and shares of olefins, aromatics, and oxygenate. For diesel fuel, the sulfur content, cetane number, and shares of aromatics and additives are important indicators.

In general, the adoption of stringent vehicle emission standards requires simultaneous fuel quality improvements. This is especially true for components such as lead in gasoline and sulfur in diesel. The first big success in fuel improvement in Beijing (also in China) was the phase out of lead in gasoline. Unleaded gasoline is a key prerequisite for Euro 1 standards to prevent poisoning of the catalyst in TWC. Since the mid-1990s, China has worked to lower the lead content in gasoline. In 1995, an investigation indicated that average lead content in gasoline in China had dropped to 0.027 g L⁻¹ (14). In 1997, the Beijing EPB banned the sale of leaded gasoline and required all gasoline sold in Beijing to have lead content below 0.013 g L⁻¹. In 1998, another investigation found that the average lead content in gasoline in Beijing was as low as ~0.005 g L⁻¹ (14).

SI Figure S4 illustrates the sulfur content limits in gasoline and diesel required for vehicle emission control technologies associated with the different emission standards. Similar to lead, a high sulfur content would poison catalysts and result in lower catalyst effectiveness. SI Figure S4 shows large reductions in sulfur from the pre-Euro 1 base case to Euro 2 requirements and from Euro 3 to Euro 4 requirements. Since 2008, the sulfur content in gasoline and diesel has dropped to 50 ppm to comply with the new Euro 4 emission standards. However, it should be noted that the rest of China is still struggling with relatively high sulfur content in diesel, for example, in several regions it can reach more than 1000 ppm (21). This will offset the effectiveness of China's effort in controlling emissions of new vehicles nationwide (currently with Euro 3 and supposed in 2011 with Euro 4).

Other components of the fuel have also been enhanced, although not as aggressively as the effort to control lead and sulfur content. For example, Beijing's new gasoline standard implemented in 2008 limits benzene content to below 2.5% (by volume) in 2004 to below 1.0% in 2008; similarly, olefin content is limited to 30% (by volume) in 2004 and below 25% in 2008 (22).

4. Penetration of Alternative Fuel Vehicles and Advanced Vehicles. Recently, alternative transportation fuels and advanced vehicle technologies have been promoted as

a means to help solve air pollution problems, reduce greenhouse gas (GHG) emissions and relieve dependence on imported oil. Beijing, again, is a pioneer within China in this area; although some demonstration programs have failed.

Dedicated compressed natural gas (CNG) buses were introduced into the Beijing bus fleet in 1999. By 2008, the number reached 4200, one of the biggest CNG bus fleets worldwide (see SI Figure S5). Accordingly, Beijing built 29 CNG fueling stations (25 in operation), with natural gas consumption of ~ 100 million m^3 a year. The recently purchased CNG buses meet Euro EEV (enhanced environmentally friendly vehicle) emission standards—more stringent than Euro 4. Dedicated CNG buses have substantially lower particle emissions and moderate-to-significantly lower NO_x emissions than diesel buses. CNG buses are also cost competitive (23). An emission factor comparison of CNG and diesel buses will be discussed later. However, the CNG bus fleet in Beijing is now facing competition from hybrid electric-diesel buses. The high growth rate ($\sim 15\%$ annually on average) of CNG buses may not be sustainable.

As mentioned above, there was a major retrofit program to convert gasoline taxis to FFVs with either gasoline or LPG. By 2003, there were ~ 45 000 LPG flexible fueled taxis in Beijing, most of which are retrofits. However, the retrofitted taxis showed little emission reduction benefit. Some conversions had adverse effects on engine power, which the drivers disliked. As a result, fewer and fewer drivers fueled their FFVs with LPG (19).

Hybrid electric vehicles (HEV), pure electric vehicles (EV), and fuel-cell vehicles (FCV) are known as advanced vehicles, also called new-energy vehicles in China. Currently, only the grid-independent (GI) HEV (e.g., Toyota Prius) is a commercially mature technology. Other technologies are still under R&D and estimated to be ready in the next 5–15 years. Compared to the smaller emission reduction potential of conventional gasoline/diesel vehicles, these advanced vehicles are classified as ultralow or zero emission vehicles. Therefore, they can play a major role in reducing vehicle emissions during the next decade. During the Beijing Olympic Games, more than 50 diesel HEVs, EVs and FCVs were demonstrated. Starting in 2009, the Ministry of Science and Technology (MOST) launched a demo program called “10 Cities Each with 1,000 Advanced Vehicles”. Eventually 13 cities participated, Beijing was one of them. At this time, most of the advanced vehicles are buses and postal or sanitation trucks in Beijing; thus the dominant technology option is hybrid electric diesel vehicles. A recent study indicated that as high as ~ 60 – 80% of new vehicles by 2030 will be advanced vehicles, the majority of which will be plug-in HEV and GI HEV (24).

5. Economic Policies. Economic policies, including taxes/fees or subsidies, are effective in stimulating earlier phase-outs of high-emitting vehicles, promoting earlier adoption of low/zero emission vehicles, and reducing the vehicle fleet's total emissions. In 2000, the State Ministry of Finance and Administration of Taxation issued a notice that a 30% reduction in the excise tax, which is $\sim 5\%$ of the vehicle price for a typical car in China, would apply to the purchase of light-duty vehicles meeting Euro 2 emission standards. Such incentives promoted the early sale of Euro 2 vehicles in 2001–2002 in Beijing.

Starting in late 2008, the Beijing EPB launched a scrapping program to phase out yellow-labeled vehicles. The owners of yellow-labeled vehicle could receive up to 6000 RMB Yuan (880 USD equivalent) for scrapping their vehicle. Thanks to the subsidy, 106 000 yellow-labeled vehicles were successfully phased out of Beijing in 2009. The subsidy has now increased to 18 000 RMB Yuan (2640 USD equivalent).

In 2009, the State Ministry of Finance issued a notice that advanced vehicles (e.g., HEV, EV, and FCV) could receive up

to 600 000 RMB Yuan of subsidy with the amount dependent on the technology and vehicle size. However, the current subsidy is only applicable to public vehicles such as buses, taxis, and trucks for postal or sanitation purposes. An expansion of the subsidy to other vehicle categories (especially passenger car) is expected in the near future.

In 2009, a study of vehicle emission fees/taxes was initiated in Beijing. Four scenarios (vehicle emission fees, vehicle emission taxes in the framework of the vehicle tax, vehicle emission taxes combined with a fuel tax, and congestion fees) were studied. For details on the study, please refer to the report (2). However, primarily due to the difficulties in the regulatory process and social pressures, it may be a while before formal vehicle emission fees/taxes will be implemented.

6. Planning of Public Transportation System. Beijing is rapidly developing a world-class public transportation system, although it is eclipsed by the fast growth of personal cars. In 1995, the bus fleet had less than 5000 buses; it now has 20 000 (SI Figure S5). In recent years, the bus fleet increased at ~ 3 – 4% annually. Due to several retrofit and scrap programs, the majority of the fleet is Euro 3 and 4 diesel buses, and Euro 3 and EEV CNG buses. Phase out of gasoline buses was started in 2005 with 1–2 years remaining until complete phase out. Within the next 5 years, hybrid electric diesel buses will become a larger feature in Beijing's bus fleet, growing quickly like the CNG buses over the past decade. In addition, bus rapid transit (BRT), a moderately rapid mass transit system with much lower infrastructure investment than subway or light rail, is also under development in Beijing.

Increasing the share of subway and light rail travel will reduce traffic congestion and lower emissions. To increase the use of public transportation, more subway and light rail lines are under construction in Beijing. In 2007, the subway and light rail system was 142 km in length; increasing to almost 200 km within a year. By 2015, ~ 560 km is planned for Beijing. If the plans are achieved, Beijing will become the city with the largest subway/light rail system in the world.

7. Temporal Traffic Control Measures. Cities holding mega-events such as the Olympic Games usually try to achieve good air quality and traffic conditions by means of a variety of strategies including temporary traffic controls. Similarly, Beijing implemented temporary transportation control measures during the 2008 Olympic Games. The major traffic controls included (1) Private vehicles could only operate on odd or even days depending on the last digit of their license plates. (2) 70% of government vehicles were ordered off the road during the event. (3) Trucks could only operate inside the Sixth-Ring Road from midnight to 6 a.m. unless they were issued special passes. (4) Most vehicles with yellow environmental labels were banned from the roads throughout Beijing. As a result, total urban vehicle kilometers traveled (VKT) was reduced by 32.0% during the Games. The average speed weighted by grid VKT increased from 25 km h^{-1} to 37 km h^{-1} during the Games. Consequently, vehicle emissions of VOC, CO, NO_x , and PM_{10} inside Beijing during the 2008 Olympics were reduced by 55.5%, 56.8%, 45.7%, and 51.6%, respectively, relative to the inventory before the Olympics. More detailed discussion of these temporal traffic controls can be found in our previous paper (9).

However, these temporal control measures suffer from huge social and economic costs, and could not be extended for use under normal conditions. Beginning in October 2008, Beijing initiated a one-year demo program to restrict drivers on one day a week by license plate number. After a year, this program was extended to 2011. This program is the subject of a big debate. Major concerns include the legality and the increasing possibility of purchasing a second vehicle. However, in a short period, a moderate reduction of vehicle emissions could be expected.

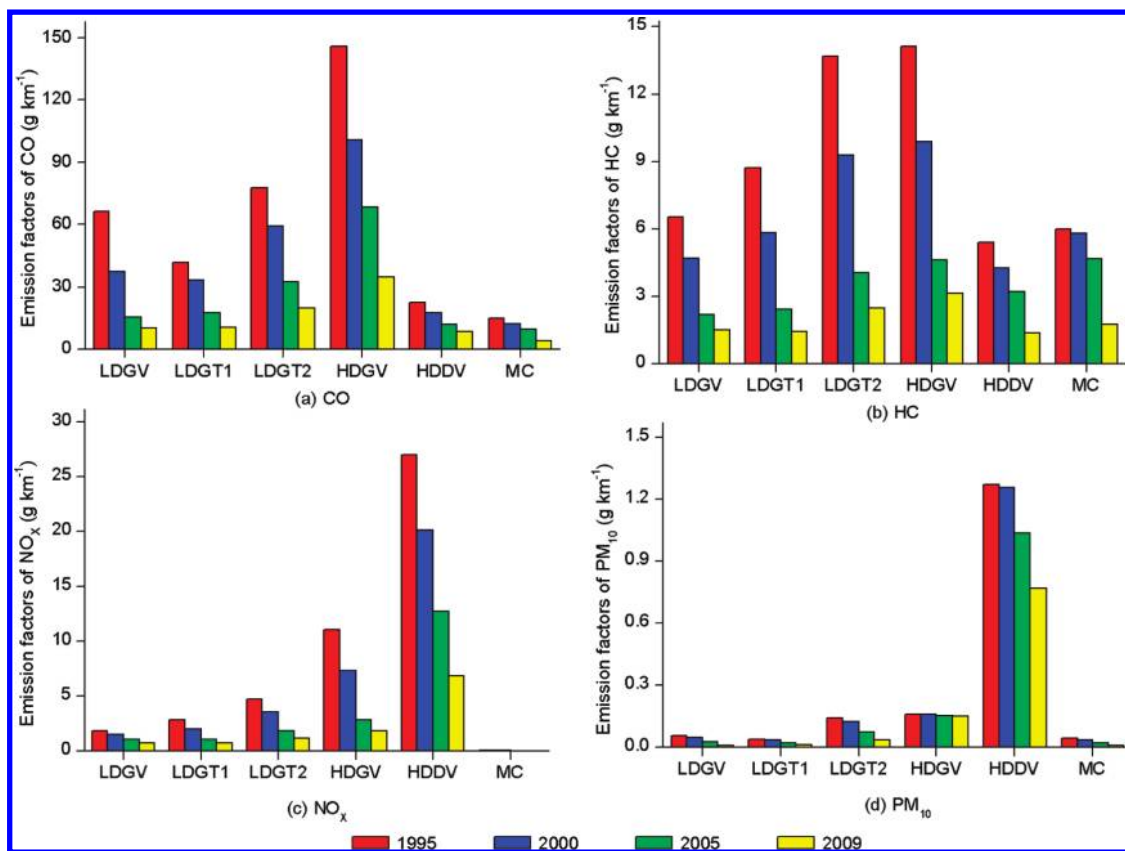


FIGURE 2. Fleet average emission factors of (a) CO, (b) HC, (c) NO_x, and (d) PM₁₀.

Assessment of Emission Reduction Benefits

1. Trends in Fleet Average Emission Factors. MOBILE-China and PART-China, two localized models based on U.S. EPA's MOBILE6, MOBILE5b, and PART5 platforms, are applied in this study to estimate vehicle emission factors by each major vehicle category in Beijing from 1995 to 2009. MOBILE-China and PART-China were first developed in 1994 (25). Since then, fleet configurations (e.g., vehicle registration distribution by major vehicle category, annual mileage accumulation rate, etc.), operational characteristics (vehicle speed, idle rate, etc.), and internal basic emission factors (e.g., zero mileage level [ZML], deterioration rate [DR], etc.) for Beijing have been modified and updated based on local research findings (3–5, 12, 14, 26). In the most recent updates for the models, a portable emission measurement system (PEMS) was used to develop second-by-second speed-dependent emission correction factors (8, 9, 27–29) and crossroad remote sensing was applied to monitor the fleet emission status (30). The application of these real-world emission measurement technologies helps improve the reliability of MOBILE-China and PART-China for applications in Beijing.

Figure 2 presents the fleet average emission factors of three gaseous air pollutants (CO, NO_x, and HC) and PM₁₀ by each major vehicle category in Beijing. Four years, i.e., 1995, 2000, 2005, and 2009, are shown next to each other for comparison. Six major vehicle categories are defined: (1) LDGV, which is set exclusively for passenger cars in this study; (2) LDGT1 (with gross vehicle weight [GVW] less than 2.7 t); (3) LDGT2 (with GVW between 2.7 and 3.8 t); (4) heavy-duty gasoline vehicle (HDGV, with GVW more than 3.8 t); (5) HDDV, and (6) MC. Not surprisingly, the fleet-average emission factors of all four pollutants by each major vehicle category clearly decrease each year. For example, LDGV in 1995 is assumed to not have any controls, consequently fleet-average emission factors are as high as 66.0 g km⁻¹ for CO, 6.5 g km⁻¹ for HC, 1.8 g km⁻¹ for NO_x, and 0.057 g km⁻¹ for

PM₁₀. However, by 2009 the emission factors drop dramatically to 10.0 g km⁻¹ for CO, 1.5 g km⁻¹ for HC, 0.8 g km⁻¹ for NO_x, and 0.008 g km⁻¹ for PM₁₀, primarily due to the implementation of Euro 1–4 emission standards, LDGV decreased fleet-average emission factors annually by 12.5% for CO, 10.0% for HC, 5.8% for NO_x, and 13.0% for PM₁₀ since 1995. It should be noted that NO_x control for LDGV is less stringent than that of other gaseous air pollutants; however, because the future Euro 5 emission standard for LDGV only tightens NO_x (CO and HC limits remain stable compared with Euro 4), the drop of NO_x emission factors for the LDGV fleet could speed up within the next 10 years.

For NO_x and PM₁₀, HDDV is the major contributor since emission factors for these two air pollutants are much higher than other vehicle categories (see Figure 2). For example, HDDV NO_x and PM₁₀ emission factors are usually 9–15 and 22–99 times as high as those of LDGV in Beijing. However, NO_x and PM₁₀ are expected to decrease significantly within the next decade because the current Euro 4 and coming Euro 5 and Euro 6 for HDDV focus primarily on controls for these two air pollutants, including requirements for both selective catalytic reduction (SCR) and diesel particulate filter (DPF) technologies. Furthermore, special attention should be paid to the bus fleet. As a competitor to the diesel bus, CNG buses in Beijing provide advantages in controlling NO_x and particles (especially the latter). SI Table S3 lists and compares the emission factors of dominant diesel and CNG bus technology options in Beijing, that is, Euro 3 diesel vs Euro 3 CNG and Euro 4 diesel vs EEV CNG. Clearly, CNG buses are 30–69% lower in NO_x and 93–97% lower in PM_{2.5} relative to their diesel counterparts. Also, use of CNG helps relieve the shortage of diesel in China. However, it should be noted that CNG buses do not help reduce greenhouse gas emissions compared to diesel buses (see SI Table S3).

Starting in late 2008, the Beijing EPB launched an extensive test program. This program includes thousands of chassis dynamometer tests for Euro 1 to Euro 4 LDGVs, and hundreds

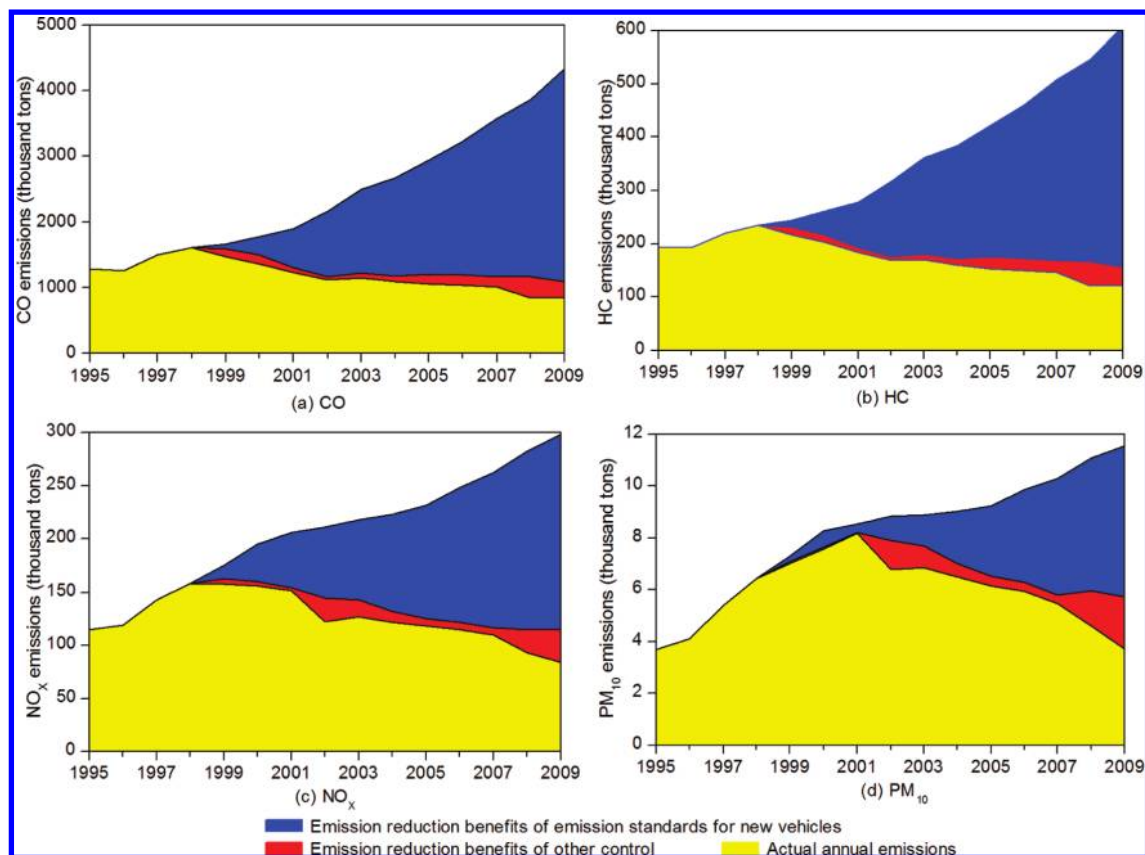


FIGURE 3. Trends in total emissions of (a) CO, (b) HC, (c) NO_x and (d) PM₁₀ for Beijing vehicle fleet with control and without control, 1995–2009.

of on-road tests for HDDVs with PEMS. As soon as these data become available, we will perform an update of our emission factor model.

2. Trends in Total Emissions from Beijing's Vehicle Fleet. With the fleet-average emission factors above and population and annual-average VKT by vehicle category, an estimate of total emissions for Beijing's vehicle fleet was calculated. Figure 3 illustrates trends in total emissions of CO, HC, NO_x and PM₁₀ for vehicle fleet in Beijing (excluding military and rural vehicles). To determine the emission reduction effects by various control strategies and policies, we design a "without control" scenario, that is, we apply pre-Euro 1 fleet-average emission factors in 1998 to the vehicle fleet in 1999–2009, also shown in Figure 3.

Before 1999, the total emissions of the four air pollutants from vehicles increased in Beijing. Total emissions of CO and HC increased by 24% and 21%, respectively, from 1995 to 1998. Increases for NO_x and PM₁₀ were even higher, 38% and 74%, respectively. For CO and HC, the reason was primarily attributed to the high growth of the LDGV population (the number of vehicles nearly tripled within three years). For NO_x and PM₁₀, it is a combination of several factors, including significant growth in both the HDDV population and weight (the latter affects particle emissions significantly), as well as a steady increase in annual VKT for HDDV. Increases in NO_x emissions were higher than CO. This is consistent with monitor readings that show near some major roads in Beijing CO increased by ~20–30% from 1991 to 1998 while NO_x increased by ~40–80% during that period (12).

Thanks to the various control strategies and policies, all four air pollutants show a clear and steady decrease in total emissions from 1999 to 2009. In 2009, total emissions of CO, HC, NO_x and PM₁₀ from the Beijing vehicle fleet were 845 000 t, 121 000 t, 84 000 t, and 3700 t, respectively. They represent significant reductions of 47%, 49%, 47%, and 42% of CO, HC, NO_x and PM₁₀, respectively, relative to 1998.

Emission standards for new vehicles are the dominant contributor to reduce the four air pollutant emissions. For CO and HC, the total emission reduction benefits by emission standard are typically more than 90%, except the first a couple of years (1999 and 2000). The relatively low reduction (~50–60% on average) in 1999–2000 can be attributed to two factors: (1) the penetration of new vehicles was short in time; and (2) there were two major control programs for in-use vehicles (retrofit of 1995–1998 light-duty vehicles and scrapping of minivan cabs). For NO_x and PM₁₀, there are two patterns. For the calendar years without major in-use control programs for HDDV (e.g., 2001, 2004–2007), the emission standards were the dominant contributor, generally accounting for more than 90% of total emission reductions. However, in 2002–2003 and 2008–2009, that decreases significantly (especially for PM₁₀) due to the implementation of enhanced scrap programs for HDDV during the two time periods (see Figure 3).

SI Figures S6 and S7 present the shares of emission reductions with major controls other than the emission standards for new vehicles in 2008 and 2009. For 2008, temporal control strategies during the Olympics and fuel quality improvements (specifically 50 ppm sulfur content) are the two leading contributors, accounting for 72–87% of total emission reduction benefits by all other major controls. In 2009, low sulfur fuel continued its major role in reducing emissions while the subsidy program for scrapping yellow-labeled vehicles was the dominant contributor to NO_x and PM₁₀ reductions, with the shares over 50%. The temporal travel restriction by license plate number (i.e., driving restrictions for one day per week) during 2009 contributed ~25%, for CO and HC, but was less significant for NO_x (16%) and PM₁₀ (4%). The reduction benefits of an enhanced I/M program with ASM test protocols are relatively stable in 2008 and 2009, accounting for ~20–25% of CO and HC reductions, ~10–15% of NO_x and ~5–10% of PM₁₀. It should be noted

that while CNG buses only account for little as 0.1% of total Beijing vehicle fleet, for NO_x and PM_{10} they account for 2–3% of total reduction benefits.

Total emissions are based on traditional top-down inventory methodologies applied with uniform emission factors by vehicle category. This methodology may not reflect real vehicle emission conditions on a relatively small scale (e.g., a busy road or the downtown area of Beijing). A more accurate grid-based or link-based vehicle emission inventory can be developed using a bottom-up approach that relies on more detailed second-by-second speed-dependent emission factors and vehicle activity data from real roads or a travel demand model (TDM). For example, TDMs used for transportation planning can provide more thorough information on the spatial distribution of roadway types, vehicle activity, and speeds along those roads. However, a discussion on this issue is beyond the scope of this paper. For additional details, refer to our other studies (9, 12, 31).

We envision a continued decrease of fleet-average emission factors for all vehicle categories in the future. For specific vehicle categories, such as LDGV, annual average VKT will also likely decrease due to the travel restriction rules and growth in private cars. However, total emissions from Beijing's vehicle fleet might not easily be reduced. A recent example is the lack of progress on total CO and HC emissions between 2002 and 2005 (see Figure 3). The difficulties come primarily from the high growth in Beijing's vehicle population (especially for LDGV). SI Figure S8 shows a projection of vehicle population (MC, military vehicles and rural vehicles are excluded) up to 2030. As many as 8.9 million (~5% of annual average growth rate) to 10.4 million vehicles (~6% of annual average growth rate) are estimated by 2030. Consequently, to offset the impacts in the growth in vehicle population and to improve air quality in Beijing, more stringent emission standards as well as other effective controls will be necessary, requiring greater wisdom of Beijing's policy-makers.

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Supporting Information Available

Tables S1–S3 and Figures S1–S8. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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