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Assessment of vehicle emission programs in China during 1998–2013: Achievement, challenges and implications☆

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ABSTRACT

China has been embracing rapid motorization since the 1990s, and vehicles have become one of the major sources of air pollution problems. Since the late 1990s, thanks to the international experience, China has adopted comprehensive control measures to mitigate vehicle emissions. This study employs a local emission model (EMBEV) to assess China's first fifteen-year (1998–2013) efforts in controlling vehicles emissions. Our results show that China's total annual vehicle emissions in 2013 were 4.16 million tons (Mt) of HC, 27.4 Mt of CO, 7.72 Mt of NO_X, and 0.37 Mt of $PM_{2.5}$, respectively. Although vehicle emissions are substantially reduced relative to the without control scenarios, we still observe significantly higher emission density in East China than in developed countries with longer histories of vehicle emission control. This study further informs China's policy-makers of the prominent challenges to control vehicle emissions in the future. First, unlike other major air pollutants, total NO_X emissions have rapidly increased due to a surge of diesel trucks and the postponed China IV standard nationwide. Simultaneous implementation of fuel quality improvements and vehicle-engine emission standards will be of great importance to alleviate NO_X emissions for diesel fleets. Second, the enforcement of increasingly stringent standards should include strict oversight of type-approval conformity, in-use complacence and durability, which would help reduce gross emitters of $PM_{2.5}$ that are considerable among in-use diesel fleets at the present. Third, this study reveals higher HC emissions than previous results and indicates evaporative emissions may have been underestimated. Considering that China's overall vehicle ownership is far from saturation, persistent efforts are required through economic tools, traffic management and emissions regulations to lower vehicle-use intensity and limit both exhaust and evaporative emissions. Furthermore, in light of the complex technology for emerging new energy vehicles, their real-world emissions need to be adequately evaluated before massive promotion.

1. Introduction and background

Outdoor air pollution has been identified as a serious risk to public health, including the cancer-causing effect concluded by the World Health Organization (Benbrahim-Tallaa et al., 2012) associated with other adverse impacts such as weakening visibility, damages to agricultural production and impacts on the climate system (Walsh, 2014; Shindell et al., 2011). Among all emitting sectors, on-road vehicles are one of the most significant sources among many developed countries (Maykut et al., 2003; Querol et al., 2007). To alleviate the environmental burden from soaring vehicle use, emission control actions have been initiated in developed countries since the 1970s. For example, in the US, the regulation of vehicle emission control substantially started with the passage of the US Clean Air Act of 1970 (US EPA, 2015a), which is seen as the beginning moment of control of vehicle emissions in the world, followed by the Europe since 1980s (Uherek et al., 2010). In the US, total vehicle emissions of major pollutants (e.g., carbon monoxide, CO; hydrocarbon, HC; nitrogen oxides, NO_X; and particulate matter, PM) have presented declines since the 1970s (US EPA, 2015b). In western European countries, using France as an example, total on-road vehicle emissions peaked around 1980 for

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CO and HC, 1990 for NO_X and 1995 for PM (Uherek et al., 2010), despite diesel NO_X emissions remaining as a significant threat (Carslaw et al., 2011; Yang et al., 2015a).

As the largest emerging economy during this period, China's vehicle stock began to rapidly increase from mid-1990s as it was associated with the rapid social-economic development (e.g., income growth, transportation infrastructure, domestic auto industry). This has created severe air pollution problems particularly in vehicle-populated cities as early as in the 1990s (Hao et al., 2001). Beijing, a pioneer city in controlling vehicle emissions within China, banned the sale of leaded gasoline in January 1998 and started implementing the China 1 emission standard (equivalent to the Euro 1 standard) for gasoline cars in January 1999 (Wu et al., 2011;, Wang et al., 2010; Zhang et al., 2014a). Therefore, these actions prior to 2000 were regarded as the starting point of the substantial vehicle emission control programs for vehicles in China. Later, comprehensive emission control policies and measures were implemented nationally. As summarized in Table 1, the emission control programs primarily consist of increasingly stringent new vehicle emissions and fuel quality requirements (see Tables S1 and S2), inspection and maintenance (I/M) programs for in-use vehicles, scrappage programs for high-emitters (e.g., yellow-labelled vehicles) or older vehicles, promotion of alternative fuel vehicles (Zhang et al., 2014b, 2014c), traffic management (Zhang et al., 2014d) and economic incentives.

Nevertheless, two significant distinctions between China and the developed countries cannot be ignored. First, unlike the developed countries where vehicle markets were mature and close to saturation levels in the 1980s (e.g., US) (World Bank Group, 2015), China has been simultaneously dealing with its fast-growing vehicle market and reducing emissions over the past fifteen years. China's vehicle population (motorcycles included) has climbed from 35 million in 1998 to 231 million in 2013 (see Fig. 1) (NBSC, 2015), primarily attributed to the surge of light-duty passenger vehicles (LDPVs) with an average annual growth up to 23%, which further secured China as the largest automobile market since 2009. Second, due to the inherently spatial heterogeneity in China concerning population density and social-economic development, we can clearly observe significant gaps in motorization levels (e.g., GDP per capita vs. LDPV ownership rate, see Fig. S1) and enforcement of vehicle emission controls between developed cites and laggard regions. For example, ultra-low sulfur gasoline and diesel fuels (i.e., sulfur content below 10 ppm) have been fully available in Beijing since May 2012 to support its further implementation of China 5/V emission standards. By contrast, the actual sulfur content of on-road diesel fuels in other regions could be as high as

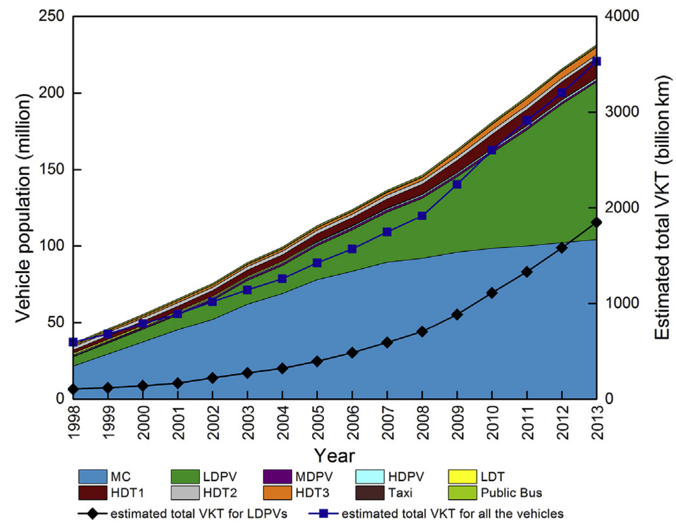

Fig. 1. Trends of registered vehicle population and estimated VKT in China, 1998–2013. Note: The dentition and abbreviation of each vehicle category is summarized in Table 2.

Table 1
Summary of major vehicle emission control measures in China, 1998–2013.

Control category	Content	Implementation scale
Control of new vehicles	(1) Implementation of increasingly stringent emission standards for new vehicles (see Table S1 for details)	Nationwide; some regions and cities (e.g., Beijing, Shanghai) implement standards earlier than the national requirements.
	(2) License restrictions on the registration of newly purchased cars (i.e., known as license control policy)	Seven cities including all the Tier 1 cities (e.g., Shanghai, Beijing, Guangzhou, Shenzhen)
Control of in-use vehicles	(1) Environmental labeling management (Pre-Euro 1 LDGVs and Pre-Euro III HDDVs are typically issued with yellow labels, indicated as high-emitters)	Nationwide; At the city-level, driving restrictions similar to low emission zones are enforced for yellow-labelled vehicles.
	(2) Scrappage and driving restrictions of high-emitting in-use vehicles	Most cities and scrappage programs recently have been accelerated by economic incentives (e.g., subsidies).
	(3) Vehicle inspection and maintenance (I/M) programs	Nationwide; Some cities employ more stringent inspection methods.
Improvement in fuel quality	(1) Ban on the sale of leaded gasoline	Nationwide
	(2) Improving fuel quality, notably the decline of sulfur content levels (See Table S2 for details)	Nationwide; Some regions and cities lead the schedule of reducing fuel sulfur content.
Penetration of alternative fuels and advanced vehicles	(1) Promoting alternative fuel vehicles in public fleets (2) Purchase subsidies and tax reduction of personal purchased new energy vehicles	Certain cities with purchase subsidies available from both central and local governments.
Transportation policy and traffic management	(1) Developing public transit systems including rail-based trains and ground buses	Certain cities
	(2) Driving restrictions on certain fleets (e.g., trucks, motorcycles or non-local fleets), typically within urban areas	
	(3) Driving restrictions on private vehicles by prohibiting driving one weekday per week	e.g., Beijing, Tianjin
	(4) Driving restrictions during major events	e.g., 2008 Beijing Olympic Games, 2010 Guangzhou Asian Games
Economic policies	(1) Subsidies for purchases of new energy vehicles (2) Subsidies for scrapping older vehicles (3) Increased parking fees	Certain cities

Note: Throughout the manuscript, with respect to regulations adopted in Europe and China, Arabic numerals are used to refer to light-duty vehicle emission standards, while Roman numerals are used to refer to heavy-duty vehicle emission standards. For the California LEV III standard, we use the Roman numeral, whilst it is for light-duty vehicles.