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On-road vehicle emissions and their control in China: A review and outlook

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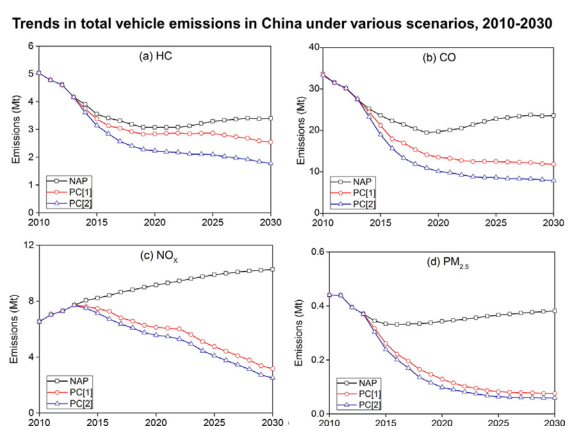
HIGHLIGHTS

- Vehicle emission controls in China are reviewed including measures related to vehicle, fuel, traffic and economic aspects.
- Total vehicle emissions have peaked and are now decreasing despite increasing vehicle population.
- Policy suggestions are provided for China's vehicle emission controls during the mid-term future.
- Tightening standards, lowering usage and promoting electrification are essential to reduce hydrocarbon emissions.
- After-treatment devices with proper in-use programs can greatly reduce emissions of nitrogen oxides and particulate matters.

GRAPHICAL ABSTRACT



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ABSTRACT

The large (26-fold over the past 25 years) increase in the on-road vehicle fleet in China has raised sustainability concerns regarding air pollution prevention, energy conservation, and climate change mitigation. China has established integrated emission control policies and measures since the 1990s, including implementation of emission standards for new vehicles, inspection and maintenance programs for in-use vehicles, improvement in fuel quality, promotion of sustainable transportation and alternative fuel vehicles, and traffic management programs. As a result, emissions of major air pollutants from on-road vehicles in China have peaked and are now declining despite increasing vehicle population. As might be expected, progress in addressing vehicle emissions has not always been smooth and challenges such as the lack of low sulfur fuels, frauds over production conformity and in-use inspection tests, and unreliable retrofit programs have been encountered. Considering the high

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Air pollution
China

emission density from vehicles in East China, enhanced vehicle, fuel and transportation strategies will be required to address vehicle emissions in China.

We project the total vehicle population in China to reach 400–500 million by 2030. Serious air pollution problems in many cities of China, in particular high ambient $PM_{2.5}$ concentration, have led to pressure to accelerate the progress on vehicle emission reduction. A notable example is the draft China 6 emission standard released in May 2016, which contains more stringent emission limits than those in the Euro 6 regulations, and adds a real world emission testing protocol and a 48-h evaporation testing procedure including diurnal and hot soak emissions. A scenario (*PC[1]*) considered in this study suggests that increasingly stringent standards for vehicle emissions could mitigate total vehicle emissions of HC, CO, NO_X and $PM_{2.5}$ in 2030 by approximately 39%, 57%, 59% and 79%, respectively, compared with 2013 levels. With additional actions to control the future light-duty passenger vehicle population growth and use, and introduce alternative fuels and new energy vehicles, the China total vehicle emissions of HC, CO, NO_X and $PM_{2.5}$ in 2030 could be reduced by approximately 57%, 71%, 67% and 84%, respectively, (the *PC[2]* scenario) relative to 2013. This paper provides detailed policy roadmaps and technical options related to these future emission reductions for governmental stakeholders.

1. Introduction and background

China's vehicle population has increased dramatically over the past two decades as a result of the rapid social-economic development and urbanization. China's gross domestic production (GDP; see all the abbreviations in the supplementary information) per capita, urbanization rate and total length of highways increased substantially from 1990 to 2014. Over the same time, China's total vehicle population (excluding rural vehicles) increased from 5.5 million in 1990 to 148 million in 2014; a 26-fold increase over 25 years (see Fig. 1) (NBSC, 2015). The total registered population of gasoline motorcycles and mopeds in China now exceeds 100 million and is approaching saturation (NBSC, 2015). China's domestic auto industry, including joint-ventured brands with international players, has gained substantial development and benefits from the growing domestic auto market that surpassed the US in volume and became the largest market in the world in 2009 (CAAM, 2015). Among all vehicle categories, the increase of light-duty passenger vehicles (LDPVs) is most significant due to the surge of private motorization demand in China alongside a prevailing concept of car ownership as an important symbol of status and personal identity.

Vehicle ownership density is a widely used indicator of the stage of motorization. China's vehicle ownership density exceeded 100 vehicles per thousand people (we use the same unit henceforth) in 2014. This is a critical point in time suggesting a further boost of vehicle stock to come through 2030. In Japan and Korea it took only twelve years (1966 to 1978 for Japan, and 1991 to 2003 for Korea) for national vehicle ownership densities to increase from 100 to 300 (World Bank Group, 2015). Researchers have estimated that total vehicle population in China would increase to 390–540 million in 2030 (Huo and Wang, 2012; Wang et al., 2011a; Wu et al., 2012a), representing vehicle ownership density of 250–380. Vehicle ownership density varies greatly between different regions in China, for example, ~250 in Beijing versus 70 in Guizhou in 2014 (NBSC, 2015). The spatial heterogeneity of vehicle ownership density implies that vehicle growth in developed cities may gradually slow down, particularly in light of license control policies; by contrast, the strong momentum of motorization may continue in internal cities of China (CAAM, 2013; PWC, 2015).

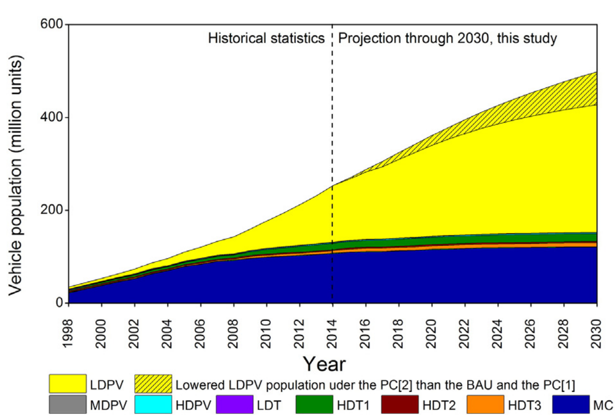

Fig. 1. Historical vehicle population (motorcycles included) by category in China and the future projections in this study, 1998–2030. Note: [a] The historical vehicle population before 2015 is from the registered population data reported in statistical yearbooks. The populations for taxis and public buses are categories into the LDPV and HDPV fleets; [b] The future projections are estimated for future scenarios, illustrated in Section 3.2. Total vehicle population in China under the *PC[1]* scenario is projected to be approximately 500 million by 2030. The current growth control measures implemented in Beijing and Shanghai are taken into account by the *PC[1]* scenario. By contrast, under the *PC[2]* scenario that would further limit total vehicle population in three developed regions, total vehicle population in China is projected to rise to approximately 430 million by 2030.

Rapid motorization poses substantial challenges for China concerning assuring energy security, mitigating regional and urban air pollution, and alleviating global climate change. China consumed 95 million tons (Mt) of gasoline and 172 Mt of diesel in 2013, increases of 167% and 152%, respectively, from 2000 (NBSC, 2014). On-road vehicles are a major driver for the surge of fuel demand accounting for approximately 90% and 45% of total gasoline and diesel consumption (CAERC, 2012). The share of imported petroleum to total oil consumption is currently approximately 60% (NBSC, 2015). It has been estimated that China's total fuel consumption by on-road vehicles could rise to 360–450 million tons of oil equivalent (toe) by 2030 (He et al., 2005; Yan and Crookes, 2009; Huo et al., 2012a), triggering concerns regarding energy security. Energy consumption by on-road vehicles has generated a substantial amount of greenhouse gas emissions. The International Energy Agency (IEA) reports that China's on-road transportation sector emitted 618 Mt of carbon dioxide (CO_2) (IEA, 2015) which is approximately 2% of global fossil fuel CO_2 emissions. Projections suggest that total on-road (tank-to-wheels) CO_2 emissions under the scenarios with high growth and no control measures might climb to approximately 1.2–1.7 billion tons of CO_2 by 2030 (He et al., 2005; Yan and Crookes, 2009; Huo et al., 2012a), and passenger transportation could contribute to approximately 0.8 billion tons of CO_2 (He et al., 2013). In November 2014, China formally submitted its climate pledge including a proposed peak in CO_2 emissions by 2030 or earlier. It is necessary for China within the time framework to make substantial progress to improve transportation system efficiency, lower energy consumption for fossil fuel powered vehicles and substantially increase the usage of low carbon on-road fuels (e.g., cleaner electricity) (Huo et al., 2012a; Wu et al., 2012a). Black carbon (BC) has been identified as an important anthropogenic short-lived climate pollutant, with diesel engines a significant source (Bond et al., 2013; Jacobson, 2001; Wang et al., 2012a). Wang et al. (2012a) estimated that total BC emissions from on-road vehicles were approximately 180 kilotons (kt), mainly from diesel vehicles. Wang et al. (2012b) and Zheng et al. (2015) have reported substantial