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The correlated impacts of fuel consumption improvements and vehicle electrification on vehicle greenhouse gas emissions in China

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ABSTRACT

Energy security and environmental issues have drawn great attentions to the energy consumption and greenhouse gas (GHG) emissions in the road transport sector. With economic development, travel demands and logistics demands will continue to rise in China. To solve the associated problems, policies related to electric vehicle (EV) promotion and fuel economy regulations are being adopted by the state government. Six scenarios, based on different policies, are analyzed to calculate vehicle fleet GHG emissions in this research by developing a bottom-up modeling framework from a life-cycle perspective. When only fuel economy regulations are considered, GHG emissions from the road transport sector will reach their peak in 2047. However, combined with EV deployment, the peak will arrive earlier, in 2026. In the short term, more stringent fuel economy regulations exhibit better results. Without EVs, fuel economy regulations will be tougher for corporations to meet than with the introduction of EVs. However, in the long term, with a higher proportion of EVs, GHG emissions will further decrease. In addition, the introduction of EVs will weaken the effects of fuel economy regulations, especially for passenger vehicles, due to credit policies. The lack of EVs in the commercial vehicle fleet will impart more significance to the fuel economy regulations. Commercial vehicles, particularly trucks, will account for the majority of GHG emissions by the whole vehicle fleet. In brief, the government should persistently focus on the fuel economy regulations to achieve an early and relatively low-level peak in vehicle fleet GHG emissions. Meanwhile, the promotion of EVs will have the long-term effect of de-carbonization. In addition, more effective measures should be taken to reduce the truck GHG emissions.

1. Introduction

Economic development has caused increased energy demand, and the burning of fossil fuels has led to a large amount of carbon dioxide emissions. China is in a stage of rapid economic development. According to the International Energy Agency (IEA), 28% of total CO_2 emissions in 2015 came from China (IEA, 2017a). China has already become the greatest source of greenhouse gas (GHG) emissions worldwide. The Chinese government has a responsibility and obligation to reduce energy consumption and GHG emissions, and therefore, the government has accordingly made efforts and commitments. Every five years, the state government in China releases a plan established for the entire country named the "Five-year Plan", which contains detailed guidelines for national economic and social development in the coming five years (Yuan and Zuo, 2011). During the 12th five-year period (2011–2015), the rate of energy consumption per unit of gross domestic product (GDP) decreased steadily, from −2.0% in 2011 to −5.6% in 2015, which led to a cumulative reduction of 18.4% over the whole period (National Bureau of Statistics of the People's Republic of China, 2015; National Development and Reform Commission and National Energy Administration, 2017). In addition, the CO_2 emissions per unit of GDP declined over 20% in the 12th five-year period, and a reduction of 18% is expected during the 13th five-year period (2016–2020) (National Development and Reform Commission and National Energy Administration, 2017). In addition, during the '2015 United Nations Climate Change Conference', the Chinese government promised to achieve a CO_2 emissions peak in China before 2030 (United Nations Climate Ch, 2015).

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The transportation sector accounted for approximately 24% of the world's CO_2 emissions from fuel combustion in 2015. For China, this value was 9.3%, which was much lower than the world average (IEA, 2017a). Road transport CO_2 emissions accounted for approximately 82.7% of the transport CO_2 emissions in the world, and the road freight generated more than 35% of transport-related CO_2 emissions (IEA, 2017a; IEA, 2017b). As the Chinese economy grows, travel and logistics demands will continue to increase (Hao et al., 2015a, 2015b). Additionally, China's dependence on foreign oil has been growing consistently each year (Yao and Chang, 2014), and therefore, controlling energy consumption and GHG emissions in the road transport sector is essential to limit the total amount of GHG emissions and ensure China's energy security.

From an international perspective, many countries have introduced the regulations and standards on vehicle fuel consumption rates to control energy consumption and GHG emissions in the road transport sector. For passenger vehicles, the European Union (EU) has set the most stringent regulations on vehicle CO_2 emissions. New passenger vehicles were required to reach a target of 130 g-CO_2/km (around 4.1 L/100 km) by 2015 and must reach 95 g-CO_2/km (around 3.0 L/100 km) by 2021 (European Commission, 2014). Japan issued new standards in 2011, which required new passenger vehicles to achieve consumption rates of 20.3 km/L (around 4.9 L/100 km) by 2020 (Ministry of Economy et al., 2011). The U.S., as the first country to enact regulations on vehicle fuel economy, updated its regulations in 2012, and demanded that new cars reach 54.5 miles per gallon (around 4.3 L/100 km) by 2025. The Chinese government also introduced the latest regulations on passenger vehicles and set targets of 5 L/100 km by 2020, 4 L/100 km by 2025 and 3.2 L/100 km by 2030 (MIIT, 2013; SAE-China, 2016). For commercial vehicles, only four countries worldwide, namely, Canada, China, Japan and the U.S., have regulations regarding fuel economy standards for heavy-duty vehicles (IEA, 2017b). For both passenger vehicles and commercial vehicles, the existence of fuel economy regulations and standards are expected to significantly promote the development of technology and solve energy-related and environmental problems.

Another effective solution to reduce energy consumption and GHG emissions is to introduce electric vehicles (EVs) into the vehicle fleet. The EV stock all over the world increased from 16.8 thousand vehicles in 2010–2014.2 thousand vehicles in 2016 (IEA, 2017c). Many countries issued different policies to stimulate the EV market from both a manufacturing perspective and a consumer perspective. The U.S. Environmental Protection Agency (EPA) introduced an incentive multiplier in fuel economy regulations for EVs based on different model years (EPA (U.S. Environmental Protection Agency), 2012). Different states in the U.S. also adopted various incentives to promote the development of EVs, such as fiscal subsidies (Zhou et al., 2015). As mentioned before, China has strong motivation to reduce its reliance on conventional fuels. In 2009, the Chinese government officially began to provide subsidies for the purchase of EVs, and some regional subsidies were also released in succession. Various subsidy standards were applied depending on regions and model years.

Most previous studies have focused on the introduction and comparison of fuel economy regulations in different countries and suggested technological strategies to meet the targets. Hao et al. and Nan et al. both introduced energy efficiency standards in China's transport sector (Hao et al., 2017; Nan et al., 2010). Li et al. analyzed vehicle fuel consumption standards and their impact on curb weight (Li et al., 2016a). Oliver analyzed the first and second fuel economy standards of passenger vehicles in China and assessed their impacts, including fuel economy improvement, technology changes, etc. (Oliver et al., 2009). Zhao et al. analyzed the fuel consumption rate target for passenger vehicles in 2020 and provided technological strategies (Zhao et al., 2016a). Above-mentioned studies only introduced the latest fuel economy regulations in China or analyzed their impacts on the vehicle models, but none of these studies illustrated the impact of fuel economy regulations on the whole vehicle fleet energy consumption or GHG emissions.

When GHG emissions are considered, few studies have focused on the importance of the latest fuel regulations. In addition, most of the researchers only pay attention to passenger vehicles while ignoring the impacts of commercial vehicles. Ou et al. mentioned fuel economy regulations. However, they did not provide specific analysis of their impacts, and only fuel economy regulations for passenger vehicles were considered in their research (Ou et al., 2010a). Yan et al. referred to fuel economy regulations on passenger vehicles and light duty commercial vehicles, and did not further analyze the influence of fuel economy regulations (Yan and Crookes, 2009). Due to the development of regulations and technologies, the validity of the results, which were based on previous regulations and data and only considered part of the vehicle fleet, will be challenged. Especially, because the latest fuel economy regulations took EVs into consideration, it is essential to re-evaluate the impact of latest regulations on vehicle fleet energy consumption and GHG emission. In addition, much attention has been paid to passenger vehicles. While, because of high fuel consumption rates, it is really also important to include commercial vehicles to make the research more objective and comprehensive.

Many scholars also analyzed the environmental impact of EVs. Qiao et al. compared the life cycle energy consumption and GHG emissions of battery electric and internal combustion engine vehicles in the vehicle production phase. (Qiao et al., 2017). The results indicated that battery electric vehicles cause 50% higher GHG emissions than internal combustion engine vehicles from a cradle-to-gate perspective. Peng et al. analyzed the life-cycle energy consumption and GHG emissions of EVs at the national level (Peng et al., 2017). Zhou et al. studied the impact of regional power grids on the GHG emissions of EVs (Zhou et al., 2013). Hao et al. considered five GHG emissions mitigation measures, which included both promoting EVs and strengthening the fuel consumption rate (Hao et al., 2011a). However, the research was only based on the passenger vehicle fleet, and the data in the research is not the most current. All in all, most studies regarding EVs are based on the individual vehicle model comparison, and the EV deployment in the latest plans in China grew faster than previous assumptions in former studies.

Studies of the vehicle fleet GHG emissions of other countries have also been conducted. Bandivadekar et al. compared the GHG emission reduction effects of different kinds of technologies in the U.S. light-duty vehicle fleet. The results indicated that the market penetration of emerging vehicle technologies should be large to realize a remarkable benefit. In the future, a combination of different kinds of technologies and incentive policies should be applied to achieve better results instead of choosing a winning technology (Bandivadekar et al., 2008). Bastani et al. also concluded that the major factors contributing to vehicle fleet GHG emissions in the U.S. would change over time from the short term to the long term and emphasized the importance of dynamic policy making (Bastani et al., 2012). Pasaoglu et al. analyzed the deployment of different powertrains for passenger vehicles and light commercial vehicles in the EU until 2050. The results show that after 2030, the technological improvement rate slowed, and the reduction of fleet GHG emissions would mainly be caused by the use of alternative fuel vehicles (Pasaoglu et al., 2012). Thus, evaluating the GHG emissions of the vehicle fleet in China is important, both to compare different solutions to GHG emissions and to make some policy recommendations for future development.

As mentioned before, there is a gap between fuel economy regulations and whole vehicle fleet GHG emissions predictions in China based on the most recent policies and data. In addition, with the deployment of EVs, fuel economy regulations have already considered EVs in China (SAC, 2014a). The introduction of EVs increases the complexity of the regulations, and EVs should be considered when the impact of fuel economy regulations is analyzed in the aspect of vehicle fleet GHG emissions. Due to the difference in EV deployment, the influence of regulations on passenger vehicles and commercial vehicles must also be discussed. Former regulations and studies both paid too much attention on the passenger vehicles and ignored the importance of the commercial vehicle fleet. A more comprehensive study is needed.

In this paper, the impact of fuel economy regulations and EV employment are analyzed in six different scenarios. The next part introduces the past, present and future fuel economy regulations and standards for different types of vehicles, and EV deployment planning in China. The third section shows the model and methods of this research. The fourth section presents the results and some discussions. The final section provides a summary of the findings.

2. Fuel economy regulations and EV deployment planning in China

Due to the impacts of technological improvements and environmental policy, fuel economy regulations in China are not periodically introduced but instead are named with Phase numbers, which indicate the order in which the regulations are introduced. When new regulations are introduced, automakers are given a period of a few months to prepare for them. Fuel economy regulations for passenger vehicles were issued first, followed by those of light-duty commercial vehicles and heavy-duty commercial vehicles. The target for passenger vehicles in the future is clearer than that for commercial vehicles, and often, a large gap exists between the draft period and the creation of official documents for commercial vehicle regulations.

2.1. Passenger vehicles

Passenger vehicles play an essential role in the whole vehicle fleet, whether in sales, stocks, or fuel consumption. Fuel economy regulations of passenger vehicles in China are divided into two parts: limits and targets, which respectively corresponding to GB 19578 and GB 27999 series (SAC, 2014a; SAC, 2004; SAC, 2011; SAC, 2014b). The standard GB19578 series regulations define the minimum requirements of China's passenger vehicle fuel consumption rates and are applied to access management of automotive products. The purpose is to eliminate outdated products and promote a decline in fuel consumption for the whole passenger vehicle fleet. A vehicle that does not meet the standard cannot be licensed, produced, sold, or registered. The standard GB27999 series regulations are based on GB19578 and introduce the fuel consumption requirement at the corporate level, denoted as the Corporate Average Fuel Consumption (CAFC). The CAFC aims to allow enterprises to adjust their product structures to meet the requirement setting aside some flexibility in individual vehicle standards.

In 2004, the first passenger vehicle fuel consumption rate limit, GB 19578-2004, was published, which included both Phase 1 and Phase 2 limits. The regulation was set based on the vehicle curb weight, as shown in Fig. 1 (a) (SAC, 2004). In 2011, the CAFC was introduced by GB 27999-2011, which regulated the fuel consumption rate target for corporations in Phase 3 (from 2012 to 2015) (SAC, 2011). In 2014, the government issued GB 19578-2014 and GB 27999-2014 together to replace former regulations GB 19578-2004 and GB 27999-2011 (SAC, 2014a; SAC, 2014b). Both the fuel consumption rate limit and target were updated according to the latest regulations. A draft of Phase 5 shows that the fuel economy regulations may change from a ladder pattern to a linear one. In Fig. 1 (a), the cross represents the fuel consumptions of newly released vehicles in 2016 on the China Average Fuel Consumption website.

The results from the analysis of successive standards show great changes, as shown in Fig. 1 (b). Between Phase 1 and Phase 2, the average annual rate of decline in each vehicle curb weight segment varies, and the trend is a concave curve as the curb weight increases. From 865 kg to 1540 kg, the average annual rates of decline are lower than 4%, while other segments, whether heavier or lighter than this segment, show greater rates of decline. By Phase 3, a significant change occurs wherein the curve becomes convex. The middle curb weight vehicles experienced relatively higher annual rates of decline. Average vehicle curb weights of the whole passenger vehicle fleet from 2012 to 2015 were all concentrated in the 1320–1430 kg segment. Thus, stricter fuel economy standards were applied to concentrated mass segments. Meanwhile, as Chinese consumers tend to buy large vehicles, controlling the fuel consumption rate of these vehicles becomes increasingly important. Unlike previous ones, the average annual rates of decline of the targets from Phase 3 to Phase 4 exhibited growth as the curb weight increased to better restrict the influence of large vehicles. In addition, the decline rates of all segments were extremely high, when compared with the previous phases.

The results brought by the introduction of fuel economy regulations are shown in Fig. 2 (SAE-China, 2016; iCET, 2017). The blue squares indicate the actual average fuel consumption rates of the whole passenger vehicle fleet over the past few years, and the red squares represent the targets set by the government for the future. The solid lines and the dotted lines respectively refer to the execution dates for newly certificated vehicles and vehicles in progress in each phase. When the rates of decline of every 5-year period are compared, great improvements are expected in the future, especially for the period from 2015 to 2020. The introduction of EVs in the regulations will ease the pressure on automakers to some extent. The New Energy Vehicle (NEV) credit can be used to compensate for the CAFC credit. The dual-credit regulations will increase enterprises flexibility to meet the targets (iCET, 2017; Liu et al., 2017). Thus, there will be some differences between the actual fuel consumption rates and the targets.

2.2. Light-duty commercial vehicles

The fuel economy standards for light commercial vehicles are applied to N1 vehicles (freight-carrying light-duty commercial vehicles) with a highest velocity over 50 km/h and M2 vehicles (passenger-carrying light-duty commercial vehicles) with masses less than 3500 kg. The regulations for light commercial vehicles have undergone major changes. Phase 1 and 2 limits were released in 2007 with GB 20997-2007, and the Phase 3 limits were released in 2015 with GB 20997-2015 (SAC, 2007; SAC, 2015). As shown in Fig. 3 and Fig. 4, the mass division in Phase 1 and Phase 2 was roughly outlined and was based on the maximum design weight and engine displacement. Whereas, in the third phase, the mass division was the same as that in the passenger vehicle regulations, and the basic also changed from the maximum design weight to the curb weight. The transformation in mass standards left few opportunities for automakers to take advantages of loopholes in the regulation, which caused the regulations to be more stringent. The difference between gasoline vehicles and diesel vehicles remained, which was conducive to the production of gasoline vehicles, while inhibiting the production of diesel vehicles.

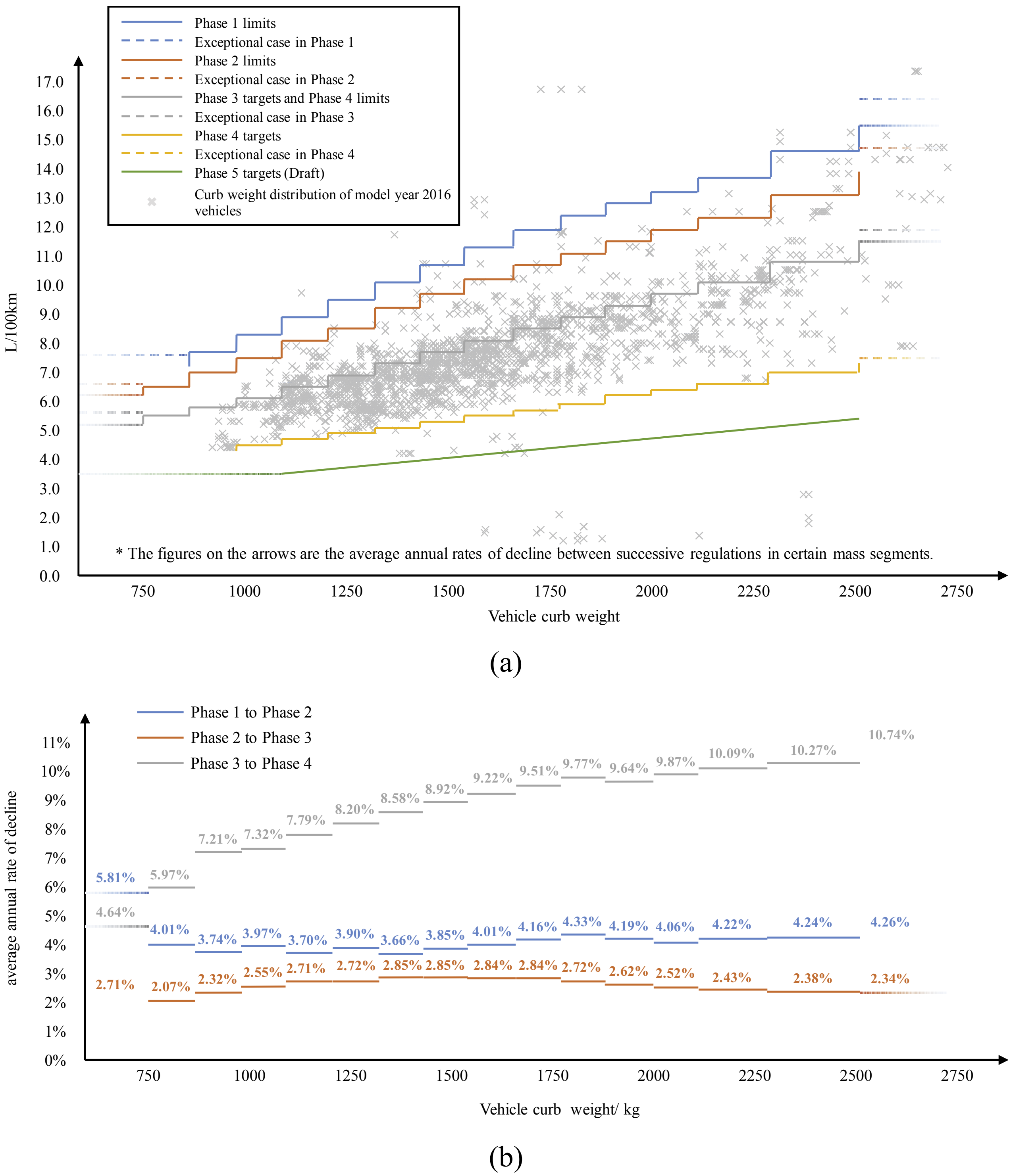


Fig. 1. Fuel economy regulations for passenger vehicles in Phases 1, 2, 3, 4 and 5 (draft) and average annual rate of declines between successive phases. (Exceptional cases includes vehicles equipped with automatic transmission, or with three or more rows of seats) (SAC, 2014a; SAC, 2004; SAC, 2011; SAC, 2014b).

2.3. Heavy-duty commercial vehicles

In China, vehicles, with a maximum design weight heavier than 3500 kg, are described as heavy commercial vehicles. For heavy commercial vehicles, unlike passenger vehicles and light commercial vehicles, fuel consumption rate limits in Phase 1 were once published as industrial standard QC/T 924—2011, and later. In Phase 2, the limits were set as a national standard in GB 30510-2014 (MIIT, 2011; SAC, 2014c). The mass division of heavy-duty commercial vehicles was based on maximum design weight, and the limits also followed a ladder pattern. In addition, dump trucks and city buses were newly introduced in Phase 2. The regulations in Phase 3 are a draft for advice and should reduce the fuel consumption rate by 15% from 2015 to 2020 on average, as Fig. 5 shows (Meng and Zhang,

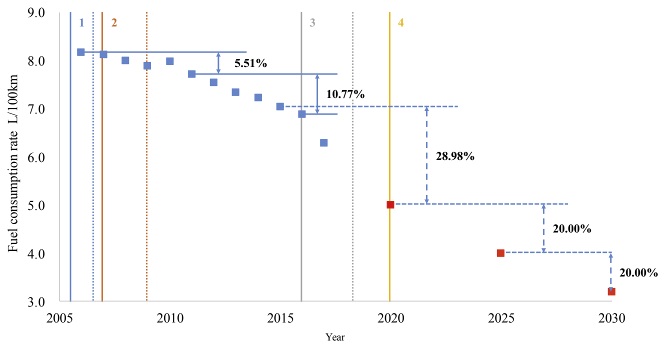


Fig. 2. Average fuel consumption rates of passenger vehicles in China from 2006 to 2017 and targets in 2020, 2025 and 2030 (iCET, 2017; Liu et al., 2017).

2017). As the design weight continues to increase, the annual rates of decline in consumption by both trucks and buses show a downward trend.

2.4. EV deployment in China

The state government has paid much attention to the deployment of EVs, including implementing subsidy policies and enacting industry planning. By 2016, the EV stock in China reached 648.8 thousand vehicles (IEA, 2017c). In 2012, the state council first issued a plan for new energy vehicles (NEV) development and noted that by 2020, the production capacity of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) should reach 2 million (The State Council of the People's Republic of China, 2017). Subsequently, the government ministries introduced several guidelines and projects to promote the development of EVs (The State Council of the People's Republic of China, 2014; NDRC, 2015; NDRC, 2017).

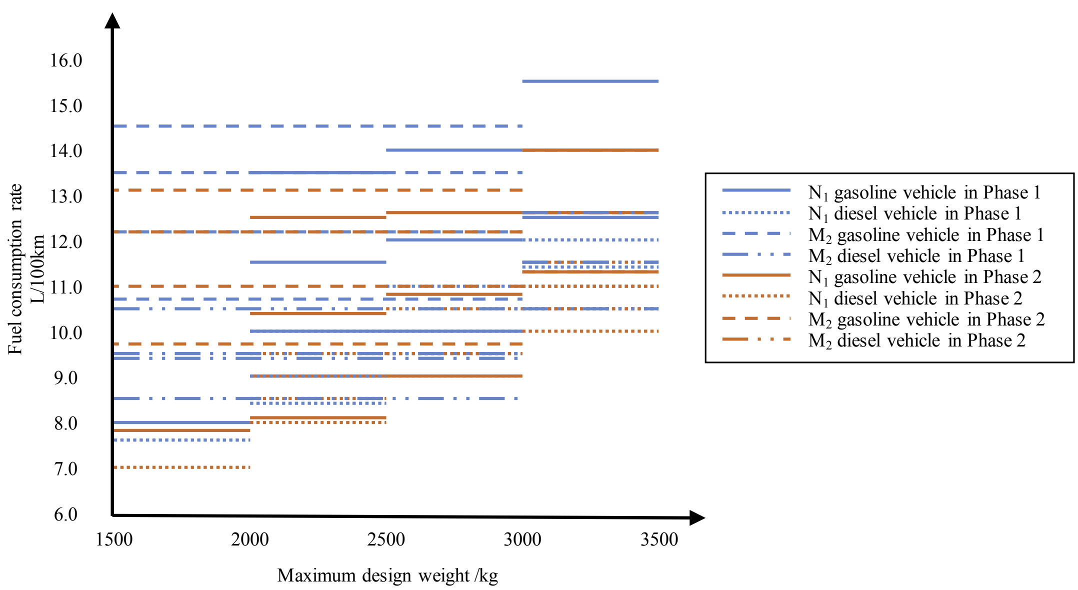


Fig. 3. Fuel economy regulations of light commercial vehicles in Phases 1 and 2 (SAC, 2007).

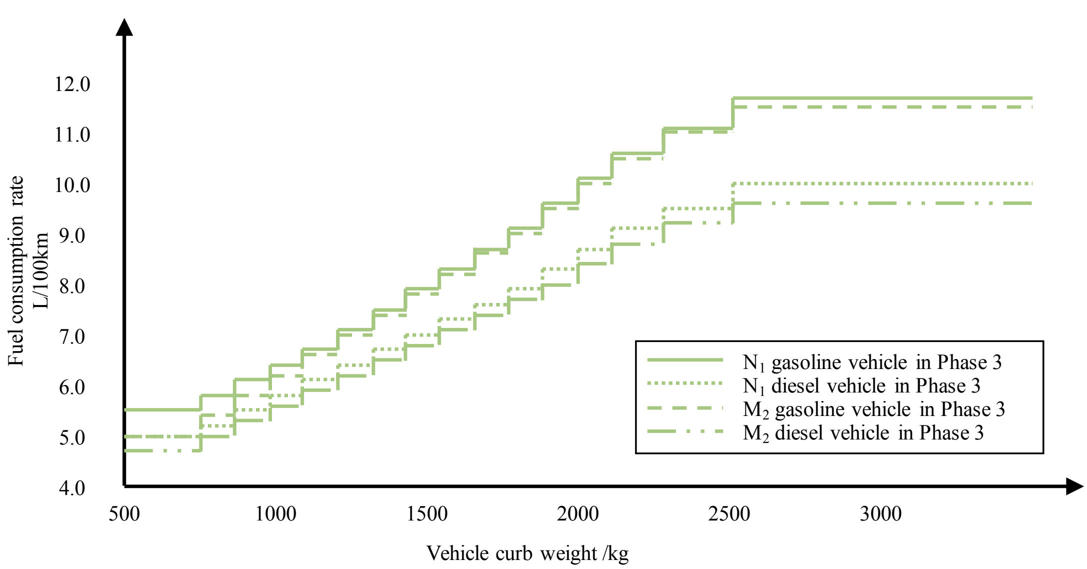


Fig. 4. Fuel economy regulations of light commercial vehicles in Phase 3 (SAC, 2015).

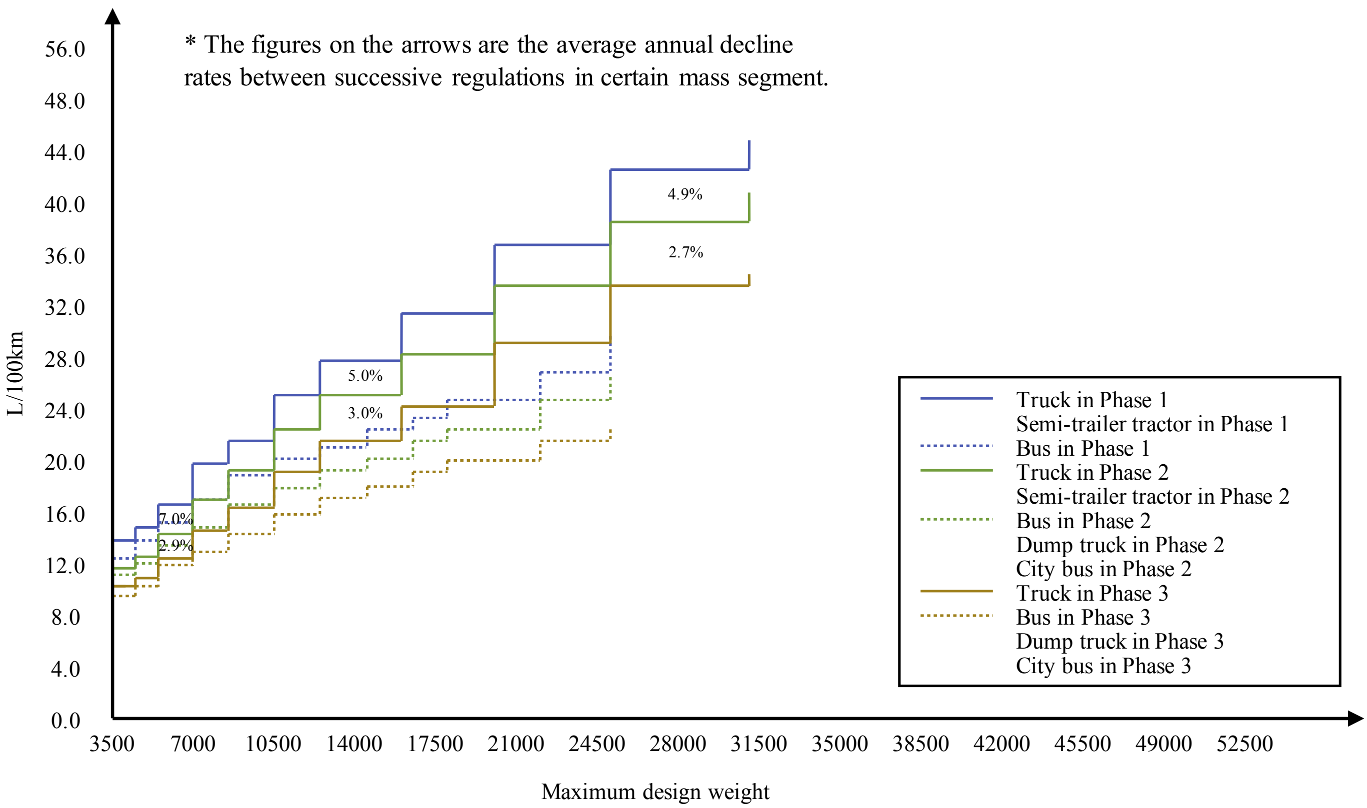


Fig. 5. Fuel economy regulations of heavy duty commercial vehicles in Phase 1, Phase 2 and Phase 3 (draft) (MIIT, 2011; SAC, 2014c; Meng and Zhang, 2017).

In 2016, SAE-China published the latest plan via the Energy-saving and New Energy Vehicles Technology Roadmap (SAE-China, 2016). According to the plan, NEVs would account for 7%, 15% and 40% in total vehicle sales in 2020, 2025 and 2030, and the NEV stock would reach 5 million, 20 million and 80 million, respectively.

To promote the development of EVs, EVs are given a special status in the CAFC in Phase 4. Electricity consumption is not taken into consideration as the fuel consumption, and EVs are weighted five times in 2016–2017, three times in 2018–2019 and twice in 2020 when production is counted (SAC, 2014a). In addition, a dual-credit mechanism can transform the NEV credit into a CAFC credit. Thus, the production of EVs will both generate NEV credit and lower the CAFC (Liu et al., 2017; Wang et al., 2018).

Table 1
Vehicle types and fuel types.

	ICE			EV		
	Gasoline	Diesel	CNG/LNG	PHEV	BEV	FCEV
PV	✓		✓	✓	✓	✓
LDB	✓	✓	✓	✓	✓	✓
MDB	✓	✓	✓	✓	✓	✓
HDB	✓	✓	✓	✓	✓	✓
MT	✓	✓	✓		✓	✓
LDT	✓	✓	✓		✓	✓
MDT		✓	✓		✓	✓
HDT		✓	✓		✓	✓

1 ICE: internal combustion engine; FCEVs: fuel cell electric vehicles.
2. Only the main fuels for each vehicle type are listed as '✓' in the table. For example, gasoline HDTs were sold before 2012, but then the market has been dominated by diesel and CNG/LNG. Thus, there is no '✓' in the table for gasoline HDTs.
3. For FCEVs, a clear outlook for their future development does not exist. Thus, though FCEVs will be introduced into the vehicle fleet gradually, its proportion in total vehicle sales will be relative low. BEVs and PHEVs will account for the main sales of EVs.

3. Methods and data

3.1. System boundary

In this study, an attempt is made to evaluate and predict the GHG emissions of the vehicle fleet, based on previous studies (Hao et al., 2011a, 2017; Zhao et al., 2016b; Wang et al., 2017). Both the up-stream phase and consumption phase of fuel/power are taken into consideration. Table 1 shows the vehicle types and powertrains analyzed in this paper. The study includes eight vehicle types: passenger vehicles (PVs), light-duty buses (LDBs), medium-duty buses (MDBs), heavy-duty buses (HDBs), mini trucks (MTs), light-duty trucks (LDTs), medium-duty trucks (MDTs) and heavy-duty trucks (HDTs). The vehicle fuels include gasoline, diesel, compressed natural gas (CNG), liquefied natural gas (LNG), electricity and hydrogen.

3.2. Methods

The life-cycle assessment (LCA) method provides an effective solution to calculate energy consumption and GHG emissions (Beer et al., 2002). For vehicles, the life cycle is usually divided into the fuel cycle and vehicle cycle (Wang, 2015). The fuel cycle includes the stages of raw material extraction, transportation, refining, product transportation and delivery for liquid or gaseous fuels, and the stages of resource exploitation, resource transportation, power generation, transmission and distribution for electricity. The vehicle cycle always involves material production, material transportation, assembly and distribution (Ou et al., 2011). In this study, only the fuel cycle is considered to provide a comprehensive comparison. Most of the previous studies are based on the same method (Hao et al., 2015a, 2015b; Ou et al., 2010a; Yan and Crookes, 2009).

The calculation of vehicle GHG emissions is shown in Equation (1) based on vehicle sales, survival rates, fuel economy and mileage, and GHG emissions intensity.

$$GHG_i = \sum_t \sum_f \left[\sum_{j=i-l_t}^{i} Sales_{t,f,j} \times SR_{t,i-j} \times VKT_t \times \left[FCR_{t,f,j} \times (1-\alpha) \times GI_f \times HV_f \times \rho_f + PC_{t,f,j} \times \alpha \times GI_{electricity} \right] \right] \quad (1)$$

where

GHG_i is the GHG emissions of the vehicle fleet in target year i (mt (million tons) CO_2 eq.);
$Sales_{t,f,j}$ is the number of sales of vehicle type t with fuel type f in year j (unit);
$SR_{t,i-j}$ is the survival rate of vehicle type t in the $(i-j)_{th}$ year (%);
$VKT_{t,i-j}$ is the mileage of vehicle type t in the $(i-j)_{th}$ year (100 km);
$FCR_{t,f,j}$ is the fuel consumption rate of vehicle type t with fuel type f in year j (L/100 km);
α is the fraction of travel distance that is powered by electricity, so $(1-\alpha)$ presents the fraction of travel distance powered by the liquid or gaseous fuel;
GI_f is the GHG emissions intensity of fuel type f used for the vehicle;
HV_f is the heat value of fuel type f used for the vehicle;
ρ_f is the density of the fuel type f used for the vehicle;
$PC_{t,f,j}$ is the power consumption of vehicle type t with fuel type f in year i (kWh/100 km);
l_t is the life span of vehicle type t;
$GI_{electricity}$ is the GHG emissions intensity of electricity.

3.3. Data

3.3.1. Vehicle sales & stock

Historical sales data of each vehicle type is obtained from the China Automotive Industry Yearbook (CATARCCAAM, 1998–2016). Due to the low vehicle ownership per thousand people in China, there is still great potential for growth. Previous researchers have provided different theories about the vehicle sales and vehicle stocks in the future (Shen, 2006; Hao et al., 2011b). The latest predictions of the industrial association show that the annual vehicle sales will reach 30, 35 and 38 million in 2020, 2025 and 2030, respectively (SAE-China, 2016). Most of the growth will be caused by passenger vehicles growth. In addition, based on historical data, the economy has great influence on the commercial vehicle sales, especially on trucks. Therefore, with a growing demand for logistics, there is no doubt that commercial vehicles sales will continuously increase. Thus, in this study, based on historical data and the most recent plan, the vehicle population will respectively reach 389, 440 and 458 million in 2030, 2040 and 2050. Both passenger vehicles and commercial vehicles will show a saturation tendency, and the annual growth rate will gradually decline.

Alternative fuel vehicles deployment is an essential part of the vehicle population. In this study, the penetration of alternative fuel vehicles follows the plan set by SAE-China and the national ministries (SAE-China, 2016; MIITNDRC, 2017). Alternative fuel vehicles will account for 7%, 15% and 40% of the total vehicles sales in 2020, 2025 and 2030, and FCEVs will reach 5 thousand, 50 thousand and 1 million, respectively. EVs will experience rapid growth and gradually dominate the market, especially as passenger vehicles. The detailed vehicle sales are shown in Fig. 6.

3.3.2. Fuel consumption rate

Historical data of passenger vehicle fuel consumption rates is obtained from iCET and announcements published by the government (iCET, 2017; MIIT, 2012). Based on the plan of SAE-China, the fuel consumption rates of the whole passenger vehicle fleet will reach 5 L/100 km, 4 L/100 km and 3.2 L/100 km in 2020, 2025 and 2030, respectively. These values are not totally dependent on the vehicle fuel economy improvement but also include the compensation effect of EVs in a dual-credit system. Further details in different scenarios will be discussed in a later section. Official statistics for the commercial vehicle fuel consumption rate do not exist. Thus, this paper comprehensively uses previous studies for references (Yan and Crookes, 2009; Hao et al., 2012; Ou et al., 2012; He et al., 2005). Future fuel economy values are projected by the assumption of annual decline rates combined with existing regulations.

3.3.3. Vehicle travel distance

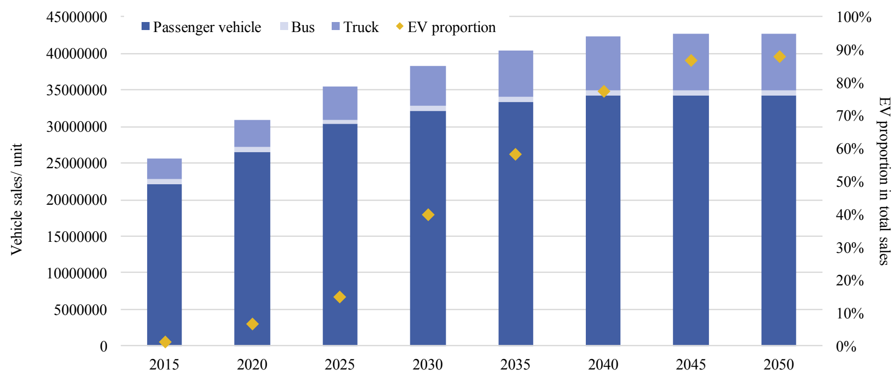
Vehicle travel distance is affected by a variety of factors, such as regional differences, goods difference, etc. The statistics used in this paper are based on data from multiple studies focused on Chinese cases, as shown in Table 2 (IEA, 2017b; Hou et al., 2013; Lin et al., 2009). Future variations in travel distance are not considered in this study.

3.3.4. Survival rate

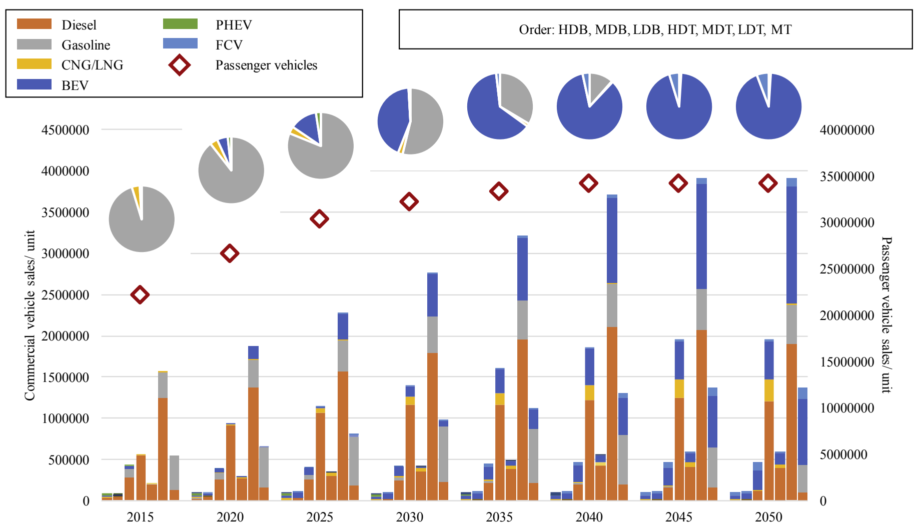
The survival rate of each type of vehicles us based on the research of Yan, as shown in Fig. 7 (Yan and Crookes, 2009). To check the reliability of the survival rate used in this research, the real and theoretical vehicle stock number are compared from 2015 to 2017. The real and theoretical values are very close. The errors between theoretical values and real data are respectively 0.71%, 0.31% and −1.00% in 2015, 2016 and 2017.

3.3.5. GHG emissions intensity

The GHG emissions intensities of conventional fuels, including gasoline, diesel and natural gas, are relatively stable, and from a life-cycle perspective, most of the GHG emissions of these fuels come from the combustion phase. Earlier studies have shown the GHG emissions intensities of conventional fuels (Ou et al., 2010a, 2010b; Samaras and Meisterling, 2008). The life-cycle GHG emissions intensity for gasoline, diesel, CNG and LNG, used in this paper is 100.8 g-CO_2 eq./MJ, 102.5 g-CO_2 eq./MJ, 69.4 g-CO_2 eq./MJ and 75.4 g-CO_2 eq./MJ. For electricity, with the development of renewable energy, the GHG intensity will continue to decline. The data used in this paper was obtained by combining GHG emissions in the generation phase and the transmissions phase, and comprehensively considering previous studies (Cai et al., 2007; Steenhof, 2007; Ang and Su, 2016). Therefore, the GHG emissions intensity of electricity in this paper is 917.2 g-CO_2/kWh for 2011 with an annual rate of decline of 2%. Because FCEVs are still deployed in pilot cities, predicting the future production pathways of hydrogen is difficult. Based on a review of the literature, steam methane reforming is currently the most cost-effective way, and in the future, the electrolysis of water powered by renewable energy should be the cleanest (Wang et al., 2013; Li et al., 2016b; Yazdanie et al., 2016; Elgowainy et al., 2018). Thus, GHG emissions in the hydrogen production stage will be gradually decline. In this paper, the GHG emissions intensity of hydrogen will drop from 200 g-CO_2/MJ in 2015, with a decrease of 3% per year.



(a)



(b)

Fig. 6. Vehicle sales and EV proportion in total sales according to the planning (SAE-China, 2016; CATARCCAAM, 1998–2016; Shen, 2006; Hao et al., 2011b; MIITNDRC, 2017).

Table 2
The life-long travel distance of each type of vehicles.

	Life-long travel distance (km)
PVs	240,000
LDBs and MDBs	500,000
HDBs	700,000
MTs	300,000
LDTs	450,000
MDTs and HDTs	600,000

3.4. Scenarios

Six scenarios are discussed in this paper, S1 to S6, as shown in Table 4. Under the business-as-usual (BAU) scenario for EV deployment, the development of EVs will follow the trend planned by the government, as shown in Fig. 6 and the vehicle stock under the BAU scenario is shown as Fig. 8 (SAE-China, 2016). Based on existing regulations in China, when CAFC is calculated, the electricity consumption of EVs is not considered, and EVs have multiple weights when determining their CAFC number. In addition, automakers can also use the NEV credit to compensate for the CAFC credit, as mentioned in the second part. In conclusion, the dual-credit mechanism will ease the pressure on automakers (iCET, 2017; Liu et al., 2017; Wang et al., 2018). With these policies, automakers can achieve the CAFC limits with a relative high fuel consumption rate for internal combustion engines with conventional fuels when combined with the production of EVs. Thus, correspondingly, the fuel consumption rate of passenger vehicles will be higher than the set standards due to the compensation effect. The impact of the dual-credit mechanism on the change in the passenger vehicle fleet fuel consumption rate used in this study is based on the research of Wang. (Wang et al., 2018). While, under a conservative EV deployment scenario, a higher proportion of EVs will not exist in vehicle sales when compared with the recent situation. Thus, the dual-credit mechanism will have little effect on the fuel economy regulations.

As for the fuel economy regulations, the BAU scenario means that the fuel consumption rate will reach the limits and targets set by the government, and all regulations and policies, including the compensation effect are taken into consideration. Under the conservative scenario, no improvements to fuel economy will occur and fuel economy will be fixed at the most recent levels. Under the optimistic scenario, the fuel consumption rates will experience aggressive improvement. For passenger vehicles, the fuel consumption rates in the optimistic scenario assumed that automakers

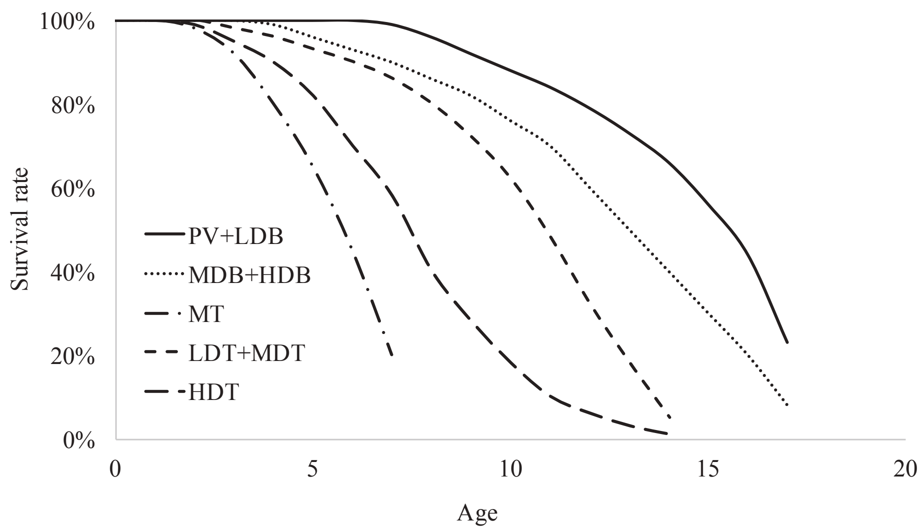


Fig. 7. Survival rates of different types of vehicles (Yan and Crookes, 2009).

Table 4
The introduction of different scenarios analyzed in this research.

	EV deployment	Fuel economy regulation
S1	BAU (following the government plan)	BAU (as shown in Fig. 9(a))
S2		Conservative (keeping at the current level-2016)
S3		Optimistic (as shown in Fig. 9(a))
S4	Conservative (keeping at the current level-2016)	BAU[a] (as shown in Fig. 9(a))
S5		Conservative (keeping at the current level-2016)
S6		Optimistic (as shown in Fig. 9(a))

[a] Due to a lack of EV deployment, the fuel consumption rate of passenger vehicles under this scenario follows the same trend as the S3.

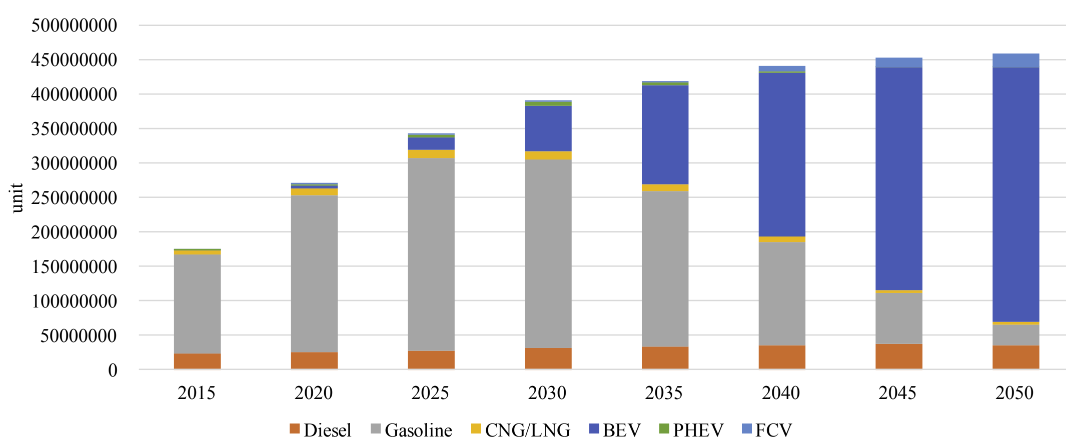


Fig. 8. Vehicle stock under the BAU scenario.

must meet the regulations without considering the compensation effect of EVs in CAFC. For commercial vehicles, there will be more rapid annual rates of decline. The fuel consumption rates for passenger vehicles and commercial vehicles under the BAU and optimistic scenarios are shown in Fig. 9(a). For figure clarity, only the consumption rates of diesel commercial vehicles are illustrated. It is based on the decline rates of fuel consumption rates in existing regulations and targets set by the government (SAE-China, 2016; SAC, 2014a; SAC, 2004; SAC, 2011; SAC, 2014b; Liu et al., 2017; SAC, 2007; SAC, 2015; MIIT, 2011; SAC, 2014c; The State Council of the People's Republic of China, 2017). The influence of the average curb weight on the fleet average fuel economy is also considered in this paper. The fuel consumption rates of EVs are shown in Fig. 9(b).

4. Results and discussion

In this sector, the comparison among different scenarios of the whole vehicle fleet, passenger vehicles and commercial vehicles are analyzed. To make the result clear and compare the proportion of GHG emissions generated by different types of vehicles, as the probable scenario, BAU scenario is discussed particularly. The final part gives the discussion about the whole result.

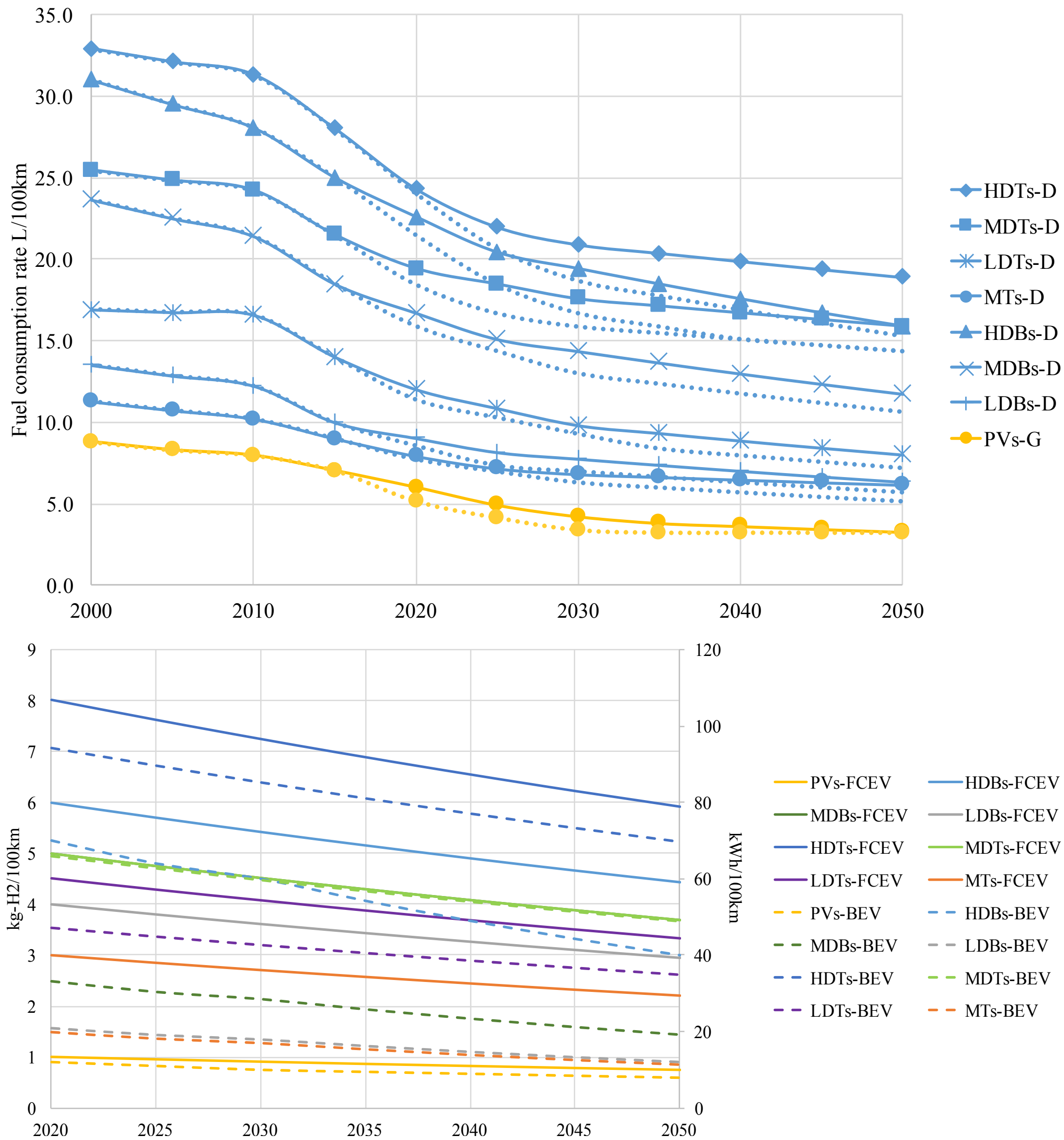


Fig. 9. The fuel consumption rate of different types of vehicles. (a)Fuel consumption rates of passenger and commercial vehicles under different scenarios. (1. HDTs-D: heavy-duty trucks-diesel; MDTs-D: medium-duty trucks-diesel; LDTs-D: light-duty trucks-diesel; MTs-D: mini-trucks-diesel; HDBs-D: heavy-duty buses-diesel; MDBs-D: medium-duty buses-diesel; LDBs-D: light-duty buses-diesel; PVs-G: passenger vehicles-gasoline, (b) Fuel consumption rates of EVs; 2. The solid lines are the fuel consumption rates under the BAU fuel consumption scenarios; the dotted lines are fuel consumption rates under optimistic fuel consumption scenarios).

4.1. Comparison among different scenarios

Due to the different proportion of EVs and different fuel economy improvement potentials in different vehicle types, the comparison among different scenarios of the whole vehicle fleet, passenger vehicles and commercial vehicles are discussed separately as follows.

4.1.1. The whole vehicle fleet

The final results of GHG emissions under each scenario are shown in Fig. 8. Under the scenarios S1, S2 and S3, the GHG emissions will peak in 2026, 2033 and 2023, respectively, with peak values of 1602.5, 2013.8 and 1500.5 mt CO_2 eq. If no improvement in EV deployment occurs, the peak time will arrive in 2047 and 2046 under scenarios S4 and S6, respectively. The GHG emissions will not peak under scenario S5.

Comparing the results of scenario S1 with scenario S2, the introduction of fuel consumption rate regulations can reduce the peak value by 20.4%. Aggressive fuel consumption rate regulations under scenario S3 will lead to an earlier GHG emissions peak time and a lower peak value, with a 6.4% improvement. Because room for improvements in fuel economy is limited, scenario S3 does not show a great difference compared with scenario S1.

The light arrows in Fig. 10 shows the difference between the scenarios including fuel economy regulations and without regulations. Obviously, the introduction of EVs reduces the importance of the fuel economy regulations. Under the ‘with EVs’ scenarios, the regulations can lead to a reduction of 21.2% of the GHG emissions in 2030 and 26.8% in 2050, while, under the ‘without EVs’ scenarios, the regulations can lead to a reduction of 41.6% in 2030 and 43.4% in 2050.

When scenario S1 is compared to scenario S4, in the short term (before 2031), scenario S1 shows a better result, which means that if no further EV deployment occurs and the automakers have to meet the fuel regulations by improving fuel consumption rates, the whole vehicle fleet GHG emissions will be lower. However, EV

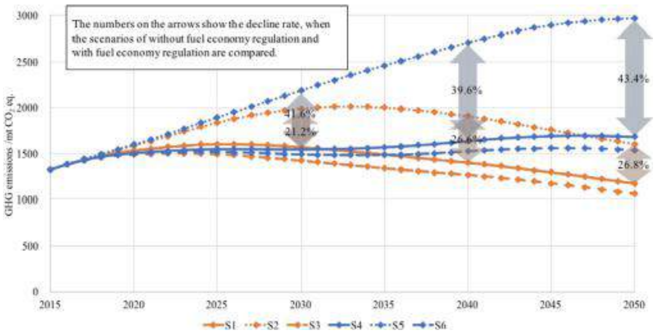


Fig. 10. The GHG emissions of the vehicle fleet under each scenario.

deployment shows a better influence over the long term, as the penetration rate of EVs increases.

4.1.2. Passenger vehicles

As for passenger vehicles, under scenarios S1, S2 and S3, the GHG emissions of the whole passenger vehicle fleet will respectively peak in 2024, 2028 and 2023, with peak values of 796.4 mt CO_2 eq., 923.5 mt CO_2 eq. and 725.9 mt CO_2 eq. With the increase of EV deployment, the effect of the fuel consumption rate regulations will gradually decline, as shown in Fig. 11. The difference between scenario S1 and scenario S2 changes from 22.2% in 2030, to 29.0% in 2040 and to 12.3% in 2050. Due to a lack of EVs, the automakers must meet the standards only by improving fuel economy. Thus, scenarios S4 and S6 show the same results, and the difference between scenarios S4 and S5 is larger and increases over time. As EV vehicle sales trend toward saturation and the fuel consumption rate reaches the lower limit, the difference gradually becomes stable. With the development of EVs, conventional fuel vehicles constitute an increasingly smaller proportion of the passenger vehicle fleet. Thus, there will be little difference among scenarios S1, S2 and S3.

4.1.3. Commercial vehicles

Commercial vehicles show totally different results compare to PVs. As the demand for logistics increases, the effect of the fuel consumption rate reduction will be offset and the GHG emissions will continue to grow, as Fig. 12 shows. Under all scenarios except S5, GHG emissions of commercial vehicles will peak in approximately 2045. Unlike passenger vehicles, there is currently no credit incentive mechanism for commercial vehicles, and thus, the penetration of EVs is relatively low. The introduction of fuel economy regulations does not initially show a large difference in the results with or without the deployment of EVs; however, over time, the difference becomes larger.

4.2. BAU scenario analysis

To more clearly illustrate the results, scenario S1 is analyzed in detail. According to the fuel economy regulations, dual-credit mechanism and the EV deployment plan, scenario S1 is the most likely to occur. As seen from Fig. 13., the introduction of EVs and fuel economy regulations will not significantly reduce the GHG emissions of commercial vehicles, and commercial vehicles will account for increasingly more emissions over time. In 2030, GHG emissions of commercial vehicles account for 55.1% of the total emissions, while in 2050, this value will increase to 82.5%. The deployment of EVs in the truck fleet, especially in the heavy-duty truck fleet, will be relatively low. In addition, significant reductions in the fuel consumption rate of heavy-duty trucks is not easy. Thus, the GHG emissions of heavy-duty trucks will not exhibit a distinct decline. For the light-duty trucks, a growing demand in logistics will generate a need and cause for increased GHG emissions and will offset the effects of the regulations. The GHG emissions generated by buses will decline, but will not have a great impact on the results as a whole.

4.3. Sensitivity analysis

As presented by Fig. 14, with the rise of EV deployment, the vehicle fleet GHG emissions decline. Generally, vehicle fleet GHG emissions in later years are more sensitive to EV deployment than earlier years. However, as the EV deployment shows saturate tendency, vehicle fleet GHG emissions changes in 2050 are little less than those in 2040, especially with high EV deployment increase. The decreases of EV deployment will have greater impact on the vehicle fleet GHG emissions than the increase. That implies the

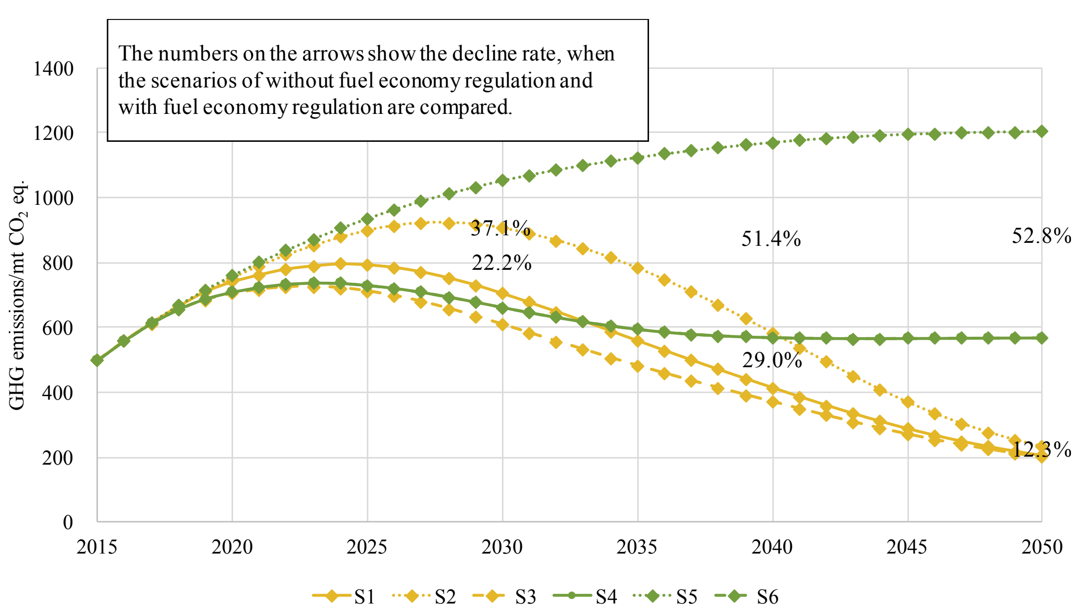


Fig. 11. The GHG emissions of passenger vehicles under each scenario.

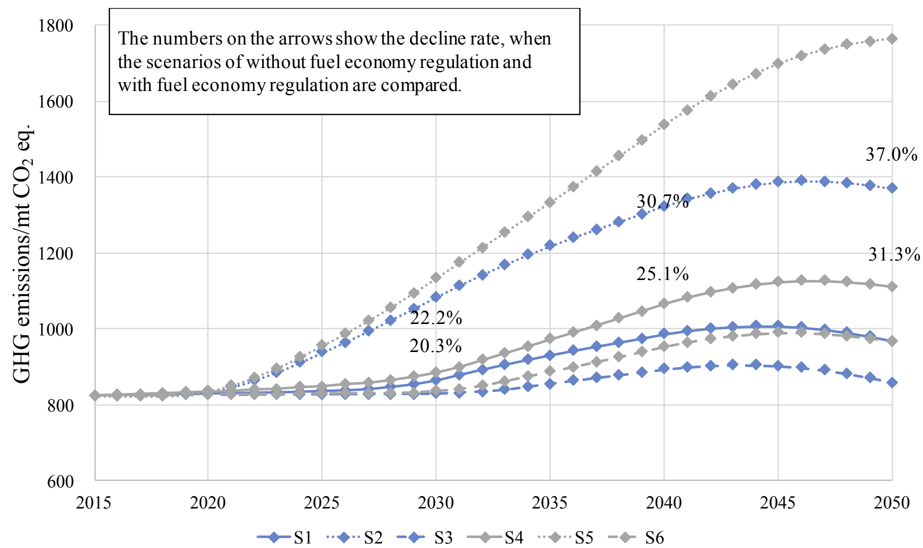


Fig. 12. The GHG emissions of commercial vehicles under each scenario.

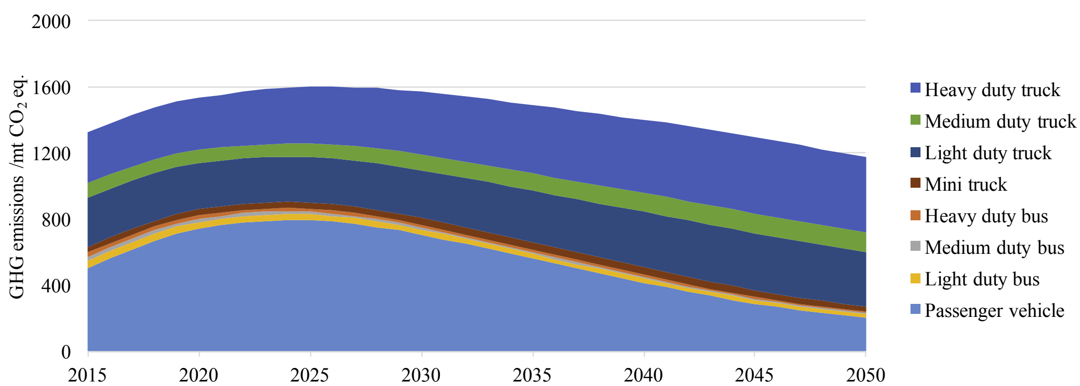


Fig. 13. The GHG emissions of different vehicle types under scenario S1.

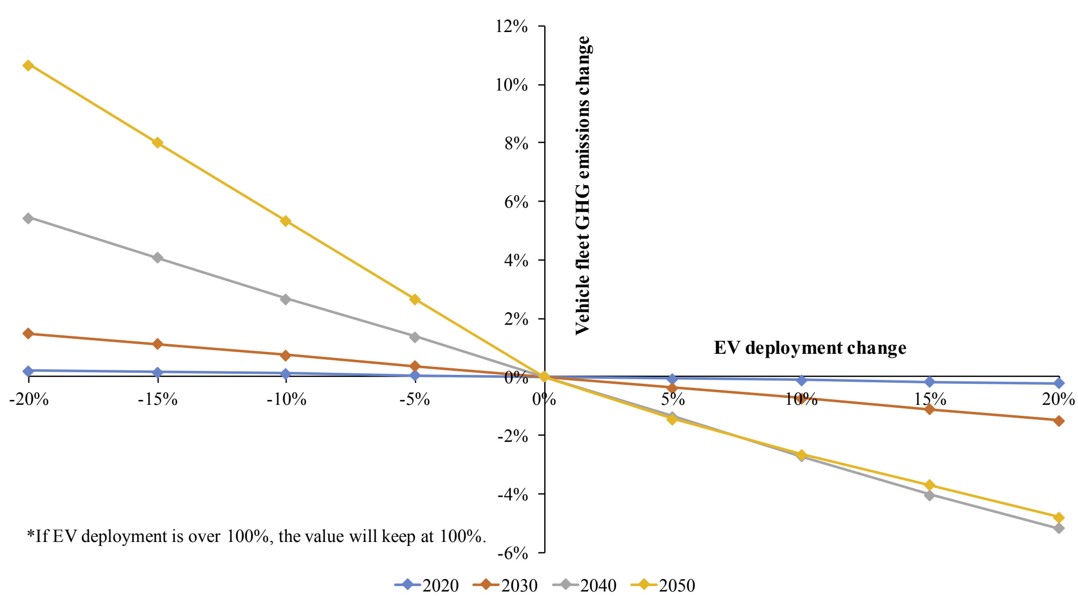


Fig. 14. Sensitivity analysis of EV deployment's effect on the vehicle fleet GHG emissions.

importance of introduction of EV in the vehicle fleet.

4.4. Discussion

Overall, introducing fuel consumption rate regulations will significantly control the GHG emissions of the whole vehicle fleet. Moreover, the deployment of EVs, to some extent, weakens the importance of the regulations. Notably, the dual-credit mechanism for passenger vehicles partly offsets the regulations and further relieves pressures placed on the automakers to reach the standards. EV deployment in commercial fleets is relatively low, and thus, applying regulations on commercial vehicles is still important.

The development of EVs in the vehicle market is an inevitable trend. However, in the short term, due to the low market penetration and high power GHG emissions intensity, more stringent fuel economy regulations will cause an earlier peak and a lower peak value. Meanwhile, in the long term, as the penetration of EVs increases and renewable energy accounts for more power generation, the development of EVs will have a greater benefit for vehicle fleet GHG emissions. Compared with other studies (Hao et al., 2015a; Zhao et al., 2010), the deployment of EVs in the latest plan is much higher than the assumptions in previous studies. Therefore, the GHG emissions of passenger vehicles in this paper are relatively low, especially in the long term, which is consistent with this study's result. Therefore, the introduction of EVs into the passenger vehicle fleet can significantly reduce future reliance on fossil fuels and future emissions. The results are also in accord with studies performed for other countries (Bandivadekar et al., 2008; Bastani et al., 2012; Pasaoglu et al., 2012).

With the increasing demand for logistics, GHG emissions from commercial vehicles will keep increasing over a long period of time. The proportion of commercial vehicles GHG emissions in the whole vehicle fleet will continue to increase. Heavy-duty trucks and light-duty trucks account for most commercial vehicle GHG emissions. Compared with the emissions of light-duty trucks, control the emissions of heavy-duty trucks is harder and more important, which is consistent with other studies, such as those by BP and Hao (Hao et al., 2012; BP, 2018). Growth in GHG emissions is stronger for trucking, with the increase in freight activities and more modest efficiency gains causing an increase in the share of emissions in the whole fleet generated by trucks to rise. In the future, the introduction of innovative technologies in the truck fleet is essential. GHG emissions of buses will gradually decline, but will still account for some proportion and will not significantly influence the whole fleet emissions.

4.4. Policy implication

In conclusion, the reduction of vehicle fleet GHG emissions in the short term will heavily depend on the application of fuel economy regulations. With the increasing popularity of EVs and the small improvement to fuel consumption rates, the deployment of EVs will overtake fuel economy regulations to become the main driving force. Thus, for the government in China, continuous implementation of and improvement to the fuel consumption rate regulations are important. Meanwhile, the deployment of EVs is an inevitable trend. Though the subsidies gradually decline in China, the introduction of new measures, such as credit mechanisms and license restrictions, will continue to promote EVs. The government should focus on a combination of different policies, rather than rely on a single policy. However, according to the results, incentive policies for EVs in fuel economy regulations will weaken the effects of the regulations on the internal combustion engine vehicles in the short term. Therefore, to promote EVs, policy makers must adopt this incentive mechanism, which will have advantages in the future.

Furthermore, although passenger vehicles currently account for approximately half of the total vehicle fleet GHG emissions, with strict fuel economy regulations and fast deployment of EVs, this proportion will gradually decline. The government has paid sufficient attention to passenger vehicles, and now, more policies should be focused on the commercial vehicles, especially trucks, both in fuel economy regulations and EV deployment. Effective solutions should be applied to reduce the GHG emissions from trucking. Therefore, incentive policies for electric commercial vehicles should be adopted to accelerate the EV development.

5. Conclusion

In this study, a bottom-up method is used to evaluate the impacts of EV deployment and fuel economy regulations on vehicle fleet GHG emissions in China from the life-cycle perspective. The synergistic influence of EV deployment and fuel economy regulations and the independent influence of fuel economy regulations are analyzed. The different scenarios for both passenger vehicles and commercial vehicles are included.

- Based on the latest fuel economy regulations and EV deployment plan, the GHG emissions of the whole vehicle fleet will peak in 2026, with a peak value of 1602.5 mt CO_2 eq.
- Fuel economy regulations have a greater impact on the peak time and peak value of the vehicle fleet GHG emissions in the short term. While, as the EV stock rises, EV deployment shows a better long-term de-carbonization effect.
- In the short term, the scenario that totally depends on the fuel economy regulations exhibits better results. In the long term, with the deployment of EVs, the impact of fuel economy regulations will fade for passenger vehicles, and with the increasing popularity of EVs, the vehicle fleet will generate much less GHG emissions.
- The government in China has paid great attention to the fuel economy of passenger vehicles in the past decades, and most EV sales are from passenger vehicles. Thus, the peak time of the GHG emissions will be reached earlier for the passenger vehicle fleet than for the entire fleet.
- Due to the little room left for fuel economy improvement and low EV deployment, commercial vehicles, especially heavy-duty trucks, will account for an increasing proportion of GHG emissions in the whole vehicle fleet. Greater efforts should be made to optimize the GHG emissions of commercial vehicles.
- The policy makers in China should continuously focus on the combination of different kinds of regulations and policies, both for fuel economy & EV deployment and passenger & commercial vehicles.
- The Chinese government should continue to control the fuel consumption rates of vehicles to reach the carbon emission peak as soon as possible. Meanwhile, the deployment of EVs is also essential for the future.

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