Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet

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\textbf{A B S T R A C T}

Passenger vehicles are the main consumers of gasoline in China. We established a bottom-up model which focuses on the simulation of energy consumptions and greenhouse gas (GHG) emissions growth by China's passenger vehicle fleet. The fuel conservation and GHG emissions mitigation effects of five measures including constraining vehicle registration, reducing vehicle travel, strengthening fuel consumption rate (FCR) limits, vehicle downsizing and promoting electric vehicle (EV) penetration were evaluated. Based on the combination of these measures, the fuel conservation and GHG emissions mitigation scenarios for China's passenger vehicle fleet were analyzed. Under reference scenario with no measures implemented, the fuel consumptions and life cycle GHG emissions will reach 520 million tons of oil equivalent (Mtoe) and 2.15 billion tons in 2050, about 8 times the level in 2010. However, substantial fuel conservation can be achieved by implementing the measures. By implementing all five measures together, the fuel consumption will reach 138 Mtoe in 2030 and decrease to 126 Mtoe in 2050, which is only 37.1% and 24.3% of the consumption under reference scenario. Similar potential lies in GHG mitigation. The results and scenarios provided references for the Chinese government's policy-making.

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1. Introduction

China's vehicle registration has experienced rapid growth over the past ten years. It increased from 14.5 million in 1999 to 62.8 million in 2009, with annual growth rate of 15.8% [1]. Passenger vehicles, which are defined as vehicles used for passenger transporting with 9 seats or fewer [2], have been growing at the fastest pace among all vehicles. The passenger vehicle registration increased from 6.3 million in 1999 to 45.9 million in 2009, with annual growth rate of 22% [1]. Passenger vehicles are the main consumers of gasoline in China. It is estimated that 48.9 million tons of gasoline were consumed by China's on-road vehicles (mostly by passenger vehicles) in 2007, accounting for 87% of China's domestic gasoline consumption [3]. The future trends of fuel consumptions and greenhouse gas (GHG) emissions by passenger vehicles are influenced by many factors including the explosive growth of vehicle registration, vehicle travel distance, the improvement of automotive technology and the government policy orientation. Numerous studies have been conducted to model these factors. Early studies started from around 2000 [4–7], when China's vehicle population entered the fast growing period. These studies mainly focused on evaluating the effect of vehicle population growth and vehicle fuel economy improvement on China's energy demand and GHG emissions. Huo et al. established a bottom-up model to simulate the growth of fuel consumptions and GHG emissions by China's vehicle fleet and evaluated the potential of fuel conservation and GHG emissions mitigation by assuming three vehicle registration growth scenarios and three fuel efficiency improvement scenarios. They projected that car registration in China would reach 91, 203 and 464 million in 2020, 2030 and 2050 (under mid vehicle growth scenario). Accordingly, total fuel consumption by cars would reach 68.3, 122.4 and 250.1 million tons in 2020, 2030 and 2050 (under mid vehicle growth and moderate fuel economy scenario). With the increasing pressure of vehicle energy supply, recent studies have evaluated a wider range of mitigation measures [8–13]. Yan et al. developed a detailed model of energy demand and GHG emissions in China's road transport sector and examined several reduction measures...
The number of newly registered TXs

for China et al. conducted a scenario analysis on alternative fuel/vehicle use promotion of diesel and gas, fuel tax and biofuel promotion. Ou including private vehicle control, fuel economy regulation, promotion of diesel and gas, fuel tax and biofuel promotion. Based on the improved model, five fuel conservation and GHG emissions mitigation measures including constraining vehicle registration, reducing vehicle travel, strengthening electric vehicle (EV) penetration were evaluated. The fuel conservation and GHG emissions mitigation scenarios for China’s passenger vehicle fleet were provided as references for the Chinese government’s policy-making.

2. Methodology

2.1. Passenger vehicle classification

In this study, we classified passenger vehicles by vehicle utility and vehicle model. By vehicle utility, passenger vehicles were classified into private passenger vehicles (PPVs), business passenger vehicles (BPVs) and taxis (TXs). PPVs are defined as passenger vehicles owned and used by individuals. BPVs are defined as passenger vehicles owned and used by enterprises and governments. By vehicle model, passenger vehicles were classified into hundreds of model categories, covering most vehicle models being sold in China. For each vehicle model, the specifications including curb weight, engine displacement and transmission type were obtained by referring to the passenger vehicle database [14]. The vehicle model-based classification was used to estimate the average fuel consumption rate (FCR) and curb weight of passenger vehicles (see Sections 3.4 and 4.4).

2.2. Model structure

A bottom-up model was established to deliver the fuel consumptions and GHG emissions by China’s passenger vehicle fleet. The model is an aggregate time-series model with prediction step of one year. The structure of the model is presented by Fig. 1.

Before 2010, the numbers of newly registered PPVs, BPVs and TXs were estimated by using vehicle production, import and export, as Equation (1) shows.

\[
NR_{i,k} = (PR_i + IM_i - EX_i) \cdot SH_i^{j,k}
\]  

(1)

where, \(NR_{i,k}\) is the number of newly registered classification \(k \) passenger vehicles in year \(i\); \(PR_i\) is the number of passenger vehicles produced in year \(i\); \(IM_i\) is the number of passenger vehicles imported in year \(i\); \(EX_i\) is the number of passenger vehicles exported in year \(i\); \(SH_i^{j,k}\) is the share of newly registered classification \(k \) passenger vehicles in all newly registered passenger vehicles in year \(i\). The determining of these terms will be introduced in Section 3.1.

After 2010, the numbers of newly registered PPVs, BPVs and TXs were derived through three steps. (a) Estimate the numbers of total registered PPVs, BPVs and TXs before 2010 by Equation (2); (b) Project the numbers of total registered PPVs, BPVs and TXs after 2010 using an elasticity model, which will be introduced in Section 4.1; (c) Estimate the numbers of newly registered PPVs, BPVs and TXs after 2010 by Equation (3).

\[
TR_{i,k} = \sum_{1980 \leq j \leq i-1} NR_{j,k} \cdot SR_{j-i,k}
\]  

(2)

\[
NR_{i,k} = TR_{i,k} - \sum_{1980 \leq j \leq i-1} NR_{j,k} \cdot SR_{j-i,k}
\]  

(3)

where, \(TR_{i,k}\) is the number of total registered classification \(k \) passenger vehicles in year \(i\); \(SR_{j-i,k}\) is the survival ratio of
classification $k$ passenger vehicles newly registered in year $j$ at age $i-j$. The total fuel consumptions and GHG emissions by the passenger vehicle fleet were delivered by Equation (4)–(6).

$$\text{IFC}_{i,m} = \sum_k \sum_{1980 \leq j \leq i} \text{NR}_{j,k} \cdot \text{SR}_{j,i-j,k} \cdot \text{SH}_{j,k}^{i,m} \cdot \text{AFCR}_{j,m} \cdot \text{APDT}_{i,k}$$

(4)

$$\text{RFC}_{i,m} = (\text{IFC}_{i-1,m} + \text{IFC}_{i,m})/2$$

(5)

$$\text{GE}_i = \sum_m \text{EF}_{i,m} \cdot \text{RFC}_{i,m}$$

(6)

where, $\text{IFC}_{i,m}$ is the indicated fuel consumption of type $m$ fuel by passenger vehicles in year $i$; $\text{SH}_{j,k}^{i,m}$ is the share of classification $k$ passenger vehicles using type $m$ fuel in all classification $k$ passenger vehicles newly registered in year $j$; $\text{APDT}_{i,k}$ is the annual per-vehicle distance traveled (APDT) of classification $k$ passenger vehicles in year $i$; $\text{RFC}_{i,m}$ is the real fuel consumption of type $m$ fuel by passenger vehicles in year $i$; $\text{GE}_i$ is the life cycle GHG emissions by passenger vehicles in year $i$; $\text{EF}_{i,m}$ is the life cycle GHG emissions factor of type $m$ fuel in year $i$.

In this study, we introduced the definition of “indicated fuel consumption” as $\text{IFC}_{i,m}$. According to Equation (4), $\text{IFC}_{i,m}$ is the fuel consumption by all passenger vehicles in year $i$ under the assumption that they are all used throughout the year. However, vehicles newly registered in year $i$ are all used less than 12 months in year $i$. $\text{IFC}_{i,m}$ is theoretically higher than the real fuel consumption in year $i$. We estimated the real fuel consumption $\text{RFC}_{i,m}$ by taking the average of $\text{IFC}_{i-1,m}$ and $\text{IFC}_{i,m}$ as Equation (5) shows.

3. Historical data

3.1. Vehicle registration

In this study, we employed vehicle production, import and export to estimate the new registration of all passenger vehicles and then estimated the new registrations of PPVs, BPVs and TXs respectively by dividing the total. The production and sales of highway vehicles in China are compiled and published by China Association of Automotive Manufacturers (CAAM). In the CAAM statistics, passenger vehicles are classified into cars, multi-purpose vehicles, sport-utility vehicles and crossovers. The import and export of vehicles in China are compiled by General Administration of Customs of PRC. Its classification is different from classification employed by CAAM. We reclassified import and export according to correspondence relationships between the two classifications [11,15,16].

The new registrations of PPVs, BPVs and TXs were estimated as follows: For TXs, we assumed that the vehicle service times are all five years. Based on this assumption, new registration of TXs can be retraced from the total registration, which can be found in China city statistical yearbook [15]. For PPVs and BPVs, we assumed that their proportions in new registrations are approximately equal to their proportions in registration increments because the number of passenger vehicles scrapped before 2010 in China was very small compared with the increment. The estimated new registrations of passenger vehicles classified by vehicle utility are presented in Fig. 2.

3.2. Survival pattern

The vehicle survival pattern describes the process that the survival ratio of vehicles decreases with the growth of vehicle age [17]. The survival pattern serves as inner mechanism of vehicle fleet upgrading and revolution in the model. China’s vehicle compulsory scrappage standard specifies the upper limits of service times and distances traveled for different classifications of vehicles. According to the latest compulsory scrappage standard which was carried out in 1997 and updated in 2000, the upper limits of service times for non-TX passenger vehicles and TXs are 15 years and 8 years. The upper limit of distance traveled for all passenger vehicles is 500,000 km. For non-TX passenger vehicles, the upper limits are permitted to be extended on condition that the vehicles meet certain performance requirements [18–20]. In this study, we employed Weibull distribution to describe the survival patterns of passenger vehicles [17], as Equation (7) shows.

$$\text{SR}_{i,j-k} = \exp\left(-\frac{(i-j)}{T_{i,k}}\right)^{S_{i,k}}$$

(7)

where, $T_{i,k}$ and $S_{i,k}$ are the characteristic parameters, which determine the vehicle average life span and vehicle scrappage intensity, respectively [17]. The parameters were estimated based on literature review, which are listed in Table 1. $S_{i,k}$ for TXs with the value of infinite represents mandatory scrappage. In the future, the survival patterns may change due to the modification of national compulsory scrappage standard or other reasons. However, we found that the projected fuel consumptions and GHG emissions are insensitive to the assumed parameters of the survival patterns. For future projection, the parameters were assumed to remain unchanged.

3.3. Vehicle propulsion system

Gasoline internal combustion engine vehicles (ICEVs) have been dominating China’s passenger vehicle market until now. In 2010, over 99% of newly registered passenger vehicles were gasoline ICEVs. Diesel ICEVs and CNG (Compressed Natural Gas) ICEVs took very little share of China’s passenger vehicle market.

3.4. Fuel consumption rate

FCR is affected by many factors including the efficiency of propulsion system, vehicle weight, vehicle condition and factors not

<table>
<thead>
<tr>
<th>Year</th>
<th>PPV</th>
<th>BPV</th>
<th>TX</th>
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<tr>
<td>1980–1990</td>
<td>20</td>
<td>20</td>
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<tr>
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<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>
related to vehicles such as driving manner and traffic flow condition. To regulate vehicle FCR, China implemented the national standard of FCR limits for passenger vehicles in 2004. The FCR limits were specified based on vehicle weight and were designed in the form of two phases, which took effect in 2006 and 2009 respectively (for under-production models) [21].

Wang et al. estimated the sales-weighted average FCR of China’s passenger vehicles based on several sources, finding that the average FCR of China’s passenger vehicles decreased from 9.11L/100 km in 2002 to 8.06L/100 km in 2006 [22]. An et al. estimated the average FCR of Chinese passenger vehicles newly registered from 2006 to 2010 by integrating the vehicle model level sales data published by China association of automobile manufacturers and FCR data announced by ministry of industry and information technology [14,16]. The average FCR of Chinese passenger vehicles was reported to decrease from 8.05L/100 km in 2006 to 7.83L/100 km in 2010 [23]. The FCR data announced by MIIT are measured over the NEDC test cycle. The actual FCR of a certain vehicle model was estimated through literature review. Ou et al. conducted a comprehensive and detailed Life Cycle Analysis (LCA) study of China’s road transportation fuels and reported the life cycle GHG emissions factors of dominating and potential transportation fuels in the Chinese context [9,25,26]. The life cycle GHG emissions factors of gasoline and diesel were estimated to be 98.9 and 102.4 g/MJ respectively. As dominating transportation fuels, gasoline and diesel are used for a long time and the efficiencies of the fuel chains are optimized. In this study, we assumed that the life cycle GHG emissions factor of gasoline and diesel would not change in the future. For electricity generation, the current life cycle GHG emissions factor was estimated to be as high as 289.6 g/MJ. This high factor should be mostly attributable to the high proportion of coal-based electricity generation in China. In 2008, coal-based thermal power accounted 80.95% of total electricity generation. It is projected that in 2020 life cycle GHG emissions factor of electricity generation in China will be reduced to 220.5 g/MJ with the development of nuclear and renewable energy and to 169.0 g/MJ if carbon dioxide capture and storage (CCS) technology is employed [26]. In this study, we assumed that the life cycle GHG emissions factor for electricity generation will decrease to 220.5 g/MJ, 208.9 g/MJ, 150.0 g/MJ in 2020, 2030 and 2050.

4. Fuel conservation and GHG emissions mitigation measures

In this paper, we presented five fuel conservation and GHG emissions mitigation measures for passenger vehicle fleet. The measures include constraining vehicle registration, reducing vehicle travel, strengthening FCR limits, vehicle downsizing and promoting EV penetration. The effects of these measures were simulated by making some assumptions in the model. As comparison, we established a reference scenario with no fuel conservation and GHG emissions mitigation measures implemented. The assumptions for the reference scenario and the measures were introduced in the sections below. It should be noted that the measure of alternative fuel use was not modeled in our study as several studies have focused on this issue and offered policy implications [9,10,25,26]. Besides, there are more potential measures of reducing fuel use by passenger vehicles than commercial vehicles. Alternative fuels are more likely to be used to replace diesel use by commercial vehicles.

4.1. Constraining vehicle registration

Constraining vehicle registration through administrative measures has been adopted in some Chinese cities like Beijing and Shanghai [8,27–31]. These policies reflect the concerns of local governments over traffic congestion, air pollution and increasing fuel demand. They have significantly slowed down the growth of local passenger vehicle registrations.

Current researches mainly focused on correlating vehicle registration growth with economy factors [5,32]. Huo et al. established a time-series model correlating vehicle stock to gross domestic product (GDP) growth. Hao et al. projected China’s passenger vehicle registration based on a resident income distribution model. In this study, we simulated the growth of vehicle registration by employing vehicle registration-GDP elasticity. Vehicle registration-GDP elasticity is defined as the percentage change of vehicle registration with a 1% change in GDP. In this study, we used Equation (8) as the approximate formula to define the elasticity.

\[ E_i = \frac{TR_i/GR_i - 1}{G_i/G_{i-1} - 1} \]  

where, \( E_i \) is the vehicle registration-GDP elasticity in year \( i \); \( G_i \) is the GDP in year \( i \).

![Fig. 3. Sales-weighted average FCR of newly registered passenger vehicles.](image-url)
4.1. Reference scenario

No nationwide policies are implemented to constrain vehicle registration and the growth of passenger vehicle registration is mainly determined by economy development. The PPV registration-GDP elasticity is 2.5, 1, 0.5 and 0.3; the BPV registration-GDP elasticity and TX registration-GDP elasticity are 0.8, 0.5, 0.3 and 0.2 during each ten-year period from 2011 to 2050.

4.1.2. Constraining vehicle registration

The effect of constraining vehicle registration was simulated by changing the assumption of the PPV registration-GDP elasticity. The PPV registration-GDP elasticity was assumed to be 0.8 times the elasticity under reference scenario. The BPV registration-GDP elasticity and TX registration-GDP elasticity were assumed to be the same with reference scenario as BPV and TX registrations are less likely to be affected by government policies. According to Equation (8), the annual GDP growth rate is the key driving factor of the elasticity under reference scenario. The BPV registration-GDP elasticity was assumed to decrease with increasing levels of vehicle ownership [10,33]. It is reported that APDT of passenger vehicles tends to decrease with increasing levels of vehicle ownership [10,33]. Compared with Japan and some European countries, the current APDT of passenger vehicles in China is relatively higher [5]. It can be attributable to two major reasons. Firstly, the urban public transit system in China is backward. It is estimated that only 20% of urban passenger transport volume is achieved by public transit system in 2010 [34]. Car travel can be hardly replaced by public transit system. Secondly, for long-distance travel, the shuttle buses and railways are less competitive than passenger vehicles in speed and comfort terms. Most private car owners would travel long distances by car rather than by bus or train.

China is making great efforts to reduce passenger vehicle use, especially to reduce private vehicle use. In terms of urban travel, better public transport is essential for reducing car use. Huge metro systems are being built in some mega cities like Beijing and Shanghai. Besides, bus rapid transit (BRT), as a low-cost and high-efficiency solution for public transit, has been adopted in some cities like Guangzhou and Shenzhen. The improved function and quality of public transit will contribute to reducing APDT of passenger vehicles in China. In terms of long-distance travel, China is building the world’s largest high-speed rail network. High-speed rail, with an average operating speed of over 300 km per hour, is competitive with private cars in speed terms. Some long-distance travel demand once met by private cars will be taken over by high-speed rails.

4.2. Reducing vehicle travel

Vehicle travel is influenced by many factors including travel demand, travel cost, traffic condition and the competition from public transport. It is reported that APDT of passenger vehicles tends to decrease with increasing levels of vehicle ownership [10,33]. Compared with development countries, the average APDT of passenger vehicles in China is relatively higher [5]. It can be attributable to two major reasons. Firstly, the urban public transit system in China is backward. It is estimated that only 20% of urban passenger transport volume is achieved by public transit system in 2010 [34]. Car travel can be hardly replaced by public transit system. Secondly, for long-distance travel, the shuttle buses and railways are less competitive than passenger vehicles in speed and comfort terms. Most private car owners would travel long distances by car rather than by bus or train.

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4.2.1. Reference scenario

In the reference scenario, the APDT of passenger vehicles decreases naturally as vehicle ownership increases. Owning to the high population density in urban areas, the APDT of China’s passenger vehicles is more likely to follow the Japan or Europe pattern, which was about 8,000 km—12,000 km in 1999 [5]. We assumed that the APDT of PPVs decrease from 15,000 km in 2010 to 12,000 km in 2020 and keep constant after that. The APDTs of BPVs and TXs will keep at the 2010 level as they are less likely to be affected.

4.2.2. Reducing vehicle travel

With substantial improvements in urban public transit and interurban mass transit systems, some private vehicle distances are replaced by subways and high-speed rails. The APDT of PPVs will decrease faster than in the reference scenario, that is, from 15,000 km in 2010 to 10,000 km in 2020 and keep constant after that. The APDTs of BPVs and TXs are the same with those in the reference scenario.

4.3. Strengthening FCR limits

The significance of strengthening FCR limits for China’s passenger vehicles has been demonstrated by several studies [35]. Compared with development countries, the average FCR of passenger vehicles in China is relatively higher. As introduced in Section 3.4, China has implemented national standard of FCR limits for passenger vehicles. The phase III limits are under discussion and will be implemented in the near future. Undoubtedly, the average FCR of passenger vehicles in China will improve under the force of the limits. Nevertheless, we assumed that FCRs of passenger vehicles are frozen under reference scenario to highlight the considerable contribution of improving FCR in reducing fuel consumptions and GHG emissions. Two points should be noted: (1) China’s current national FCR limits for passenger vehicles are weight-based with stricter limits for heavier vehicles. Average FCR is decreased due to both propulsion efficiency improvement and vehicle downsizing. To conduct single-factor analysis, we decoupled these two factors. The assumptions for strengthening FCR limits do not include the effect of vehicle downsizing. The factor of vehicle downsizing is introduced in Section 4.4. (2) The assumptions for strengthening FCR limits do not include the effect of hybrid electric vehicles (HEVs), Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) penetration.

4.3.1. Reference scenario

The FCRs of passenger vehicles are not further improved and stay at the 2010 level, which is about 9L/100 km on average for gasoline ICEVs.

4.3.2. Strengthening FCR limits

Referring to the phase III limits (exposure draft), the FCRs of newly registered passenger vehicles will decline by 20% in 2015 compared with the 2010 level. Another 15% decline of FCRs is assumed in 2020 compared with the 2015 level. According to these assumptions, the average FCR of passenger vehicles will be about...
7.2L/100 km in 2015 and 6.1L/100 km in 2020 for gasoline ICEVs. No further improvements were assumed for years after 2020.

The average FCRs of diesel ICEVs, HEVs and BEVs were assumed to be 85%, 75% and 30% of the average FCR of gasoline ICEVs (on an energy equivalent basis) [36]. The proportion of electric miles in total miles traveled for PHEVs was assumed to be 50%.

4.4. Vehicle downsizing

Passenger vehicles with smaller weights are more energy-efficient than bigger ones. Vehicle downsizing contributes to reducing the average FCR of passenger vehicle fleet. Vehicle downsizing can be achieved by producing vehicles with smaller size or lighter materials such as aluminum body. To promote the sales of smaller passenger vehicles, the Chinese government has lowered the purchase tax of passenger vehicles with engine displacements of less than 1.6L in 2009 and 2010 [37]. The penetration rates of vehicles with engine displacements of less than 1 L and 1–1.6 L in 2010 are about 14% and 51% [16]. We estimated the average curb weight of passenger vehicles by using the vehicle model level sales data published by China association of automobile manufacturers and vehicle curb weight data. We found that the average curb weight of passenger vehicles has been increasing in recent years, from about 1125 kg in 2000 to 1230 kg in 2010.

There is an approximate linear relation between vehicle weight and vehicle FCR. It is reported that for a 1445 kg passenger vehicle with FCR of 10.6 L/100 km, 4.9% and 17.7% reductions in vehicle weight can result in 2.8% and 10.4% reductions in vehicle FCR, with FCR of 10.6 L/100 km, 4.9% and 17.7% reductions in vehicle FCR, and vehicle FCR. It is reported that for a 1445 kg passenger vehicle with FCR of 10.6 L/100 km, 4.9% and 17.7% reductions in vehicle weight can result in 2.8% and 10.4% reductions in vehicle FCR, respectively [38]. Fig. 5 presents the NEDC-based FCR and vehicle curb weight for all post-2010 passenger vehicle models [14]. We conducted a linear regression and obtained the approximate relation between these two factors. The regressed factor 0.004 was used to estimate the FCR reduction effect through vehicle downsizing, as Equation (9) shows.

\[ \Delta \text{AFCR} = 0.004 \times \Delta \text{AVW} \]  

(9)

where, \( \Delta \text{AFCR} \) is the reduction of average fuel consumption rate; \( \Delta \text{AVW} \) is the reduction of average vehicle weight.

4.4.1. Reference scenario

No measures are implemented to promote vehicle downsizing. The average vehicle weight of newly registered passenger vehicles keeps unchanged at the status of 2010.

4.4.2. Vehicle downsizing

Smaller and lighter vehicles are introduced into the market. The average curb weight of newly registered passenger vehicles decreases to the level of 2000 in 2020. According to Equation (9), the average FCR of passenger vehicles will decrease by 0.42 L/100 km from 2010 to 2020 due to vehicle downsizing.

4.5. Promoting EV penetration

China is currently promoting the penetration of EVs, including HEVs, PHEVs and BEVs. The country is investing a lot of money in the research and development of EVs. Thousands of EVs are being demonstrated under a government-oriented project called “ten cities & thousand units” [39]. Besides, some private enterprises are manufacturing micro BEVs with quite low prices.

Compared with ICEVs, the average FCR of HEVs is lower but the cost is increased. The tradeoff between FCR improvement and vehicle cost defines the optimized penetration rate of HEVs. Regarding PHEVs and BEVs, there are still some arguments on whether the electric miles are cleaner than gasoline miles from the life cycle perspective due to the high proportion of coal-based electricity in China. Huo et al. conducted a region-specific research on environmental implication of electric vehicles in China. They divided China into six inter-provincial power grids with different generation mixes. They reported that in north China and northeast China, where coal-based electricity accounts for over 95% of power generation, the life cycle GHG emissions of BEVs are higher than gasoline ICEVs. In east China, central China, northwestern China and south China, where power generation is cleaner, the comparison is opposite. Power structure change is essential for reducing GHG emissions of EVs. Under current vehicle efficiency and coal-based power plant efficiency in China, a coal-based electricity share of 87% or lower is needed for EVs to achieve lower life cycle GHG emissions than gasoline ICEVs; 60% or lower is needed for EVs to achieve lower life cycle GHG emissions than gasoline HEVs [40]. With the development of low-carbon electricity in China, PHEVs and BEVs will become more beneficial in terms of fuel conservation and GHG emissions mitigation.

4.5.1. Reference scenario

The composition of newly registered passenger vehicles keeps unchanged at the status of 2010, that is, gasoline ICEVs account for about 99% of newly registered passenger vehicles.

4.5.2. Promoting EV penetration

According to the national development plan for energy-saving and new energy vehicles (exposure draft), the accumulated sales of new energy vehicles (mainly EVs) is intended to reach 0.5 million and 5 million in 2015 and 2020, respectively [41]. The ministry of science and technology established a more optimistic target, projecting that China’s EV population will reach 1 million in 2015 [42]. In this study, we simulated the measure of promoting EV penetration by referring to the national development plan target. The EV proportion in all newly registered PPVs was assumed to be 5%, 20%, 50% and 70% in 2020, 2030, 2040 and 2050. Higher EV penetration rates were assumed for BPVs and TXs because EV penetration can be further promoted by administrative requirements and demonstration projects among these vehicles. They were assumed to be 8%, 25%, 60% and 80% for BPVs and TXs, 10%, 50%, 80% and 95% for TXs in 2020, 2030, 2040 and 2050. Among all newly registered EVs, HEVs account for 70%, 40%, 20% and 0%; PHEVs account for 24%, 36%, 40% and 40%; BEVs account for 6%, 24%, 40% and 60% of the total new registration in 2020, 2030, 2040 and 2050.
5. Results

5.1. Single measure analysis

Table 2 lists the future trends of passenger vehicle registration, fuel consumptions and life cycle GHG emissions under reference scenario. Under reference scenario, the passenger vehicle registration will reach 615 million in 2050. The proportion of PPVs in all passenger vehicles will increase from 88% in 2010 to 97% in 2050. Correspondingly, the fuel consumptions and life cycle GHG emissions will reach 520 million tons of oil equivalent (Mtoe) and 2.15 billion tons in 2050, about 8.1 times the level in 2010. Gasoline will account for over 99% of total fuel consumption through 2050.

The fuel conservation effect of each measure is presented in Table 2 as well as in Fig. 6. Constraining vehicle registration and improving fuel efficiency are the two most effective measures for fuel conservation both in the near term and long term. By implementing these two measures, the fuel consumption in 2050 can be reduced by 34.0% and 32.0% respectively. Promoting EV penetration achieves a good effect of fuel conservation in the long term, with 30.2% fuel conservation and 42.0% oil conservation in 2050. However, the effect is not significant before 2030. By reducing vehicle travel, 15.1% and 15.3% reduction of fuel consumption can be achieved in 2030 and 2050. The effect of vehicle downsizing is quite limited compared with other measures, with only 5.4% reduction of fuel consumption in 2050. For all the measures, the fuel conservation effects are not significant before 2015, implying a delay between the implementation and taking effect of the measures.

The GHG emissions mitigation effects are similar with fuel conservation effects for all the measures except for promoting EV penetration due to the higher life cycle GHG emissions factor of electricity. Besides, under the measure of promoting EV penetration, the source of GHG emissions transfers from fuel combustion on vehicles to power generation in the plants. Under reference scenario, the GHG emissions from fuel combustion on vehicles account for 70.2% of life cycle GHG emissions. By promoting EV penetration, the share of GHG emissions from fuel combustion on vehicles decreases from 70.2% in 2010 to 53.5% in 2050.

### Table 2

<table>
<thead>
<tr>
<th>Registration unit: Million</th>
<th>Fuel consumptions unit: Mtoe</th>
<th>GHG emissions unit: Million ton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
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<tr>
<td><strong>Reference Scenario</strong></td>
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</tr>
<tr>
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<td>1.8</td>
</tr>
<tr>
<td>Fuel consumptions</td>
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<tr>
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<td>1.8</td>
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<tr>
<td>Gasoline</td>
<td>64</td>
<td>223</td>
</tr>
<tr>
<td>Life cycle GHG emissions</td>
<td>266</td>
<td>930</td>
</tr>
</tbody>
</table>

Fuel conservation and GHG emissions mitigation effect

- Constraining vehicle registration: 22.1%, 29.5%, 32.6%, 34.0%
- Reducing vehicle travel: 13.9%, 15.1%, 15.3%
- Strengthening FCR limits: 20.0%, 30.4%, 32.0%
- Vehicle downsizing: 3.1%, 5.0%, 5.4%
- Promoting EV penetration: 0.8%, 4.3%, 14.5%
- Oil conservation: 1.0%, 5.7%, 19.7%
- GHG emissions mitigation: 0.5%, 2.8%, 10.1%

Note: the reductions in fuel consumption and the corresponding GHG emissions are the same for the measures of constraining vehicle registration, reducing vehicle travel, strengthening FCR limits and vehicle downsizing.

5.2. Fuel conservation and GHG emissions mitigation scenarios

Among the five fuel conservation and GHG emissions mitigation measures simulated in this study, some have been on track in China like strengthening FCR limits for passenger vehicles and promoting vehicle downsizing; some have been carried out in major cities like reducing vehicle travel and constraining vehicle registration; some are more related with technology improvement and business model innovation like promoting EV penetration. Implementation of these measures will determine the future scenario of fuel consumptions and GHG emissions by China’s passenger vehicle fleet.

Fig. 7(a) presents the future scenario of fuel consumption by China’s passenger vehicle fleet. Substantial oil conservation can be achieved by implementing these measures. As two measures the Chinese government has been promoting, strengthening FCR limits and vehicle downsizing together achieve 35.4% and 37.4% reduction of fuel consumption.
consumption in 2030 and 2050 compared with reference scenario. Although with great reduction, the remaining fuel consumption will reach 240 Mtoe and 325 Mtoe in 2030 and 2050, which are about 3.7 and 5.1 times the fuel consumption in 2010. Further measures including reducing vehicle travel and constraining vehicle registration can achieve another 25.7% and 27.3% reduction of fuel consumption in 2030 and 2050. Even then, the total fuel consumption will keep an increasing trend through 2050. By promoting EV penetration, 8.6 Mtoe and 79.6 Mtoe of oil can be replaced by 2.1 Mtoe and 22.4 Mtoe of electricity in 2030 and 2050 and the increasing trend of oil consumption can be stopped by around 2030. By implementing all five measures together, the oil consumption will reach 136 Mtoe in 2030 and decrease to 104 Mtoe in 2050, which are about 36.6% and 20% of the consumptions under reference scenario.

Fig. 7(b) presents the future scenario of GHG emissions by China’s passenger vehicle fleet. The pattern of GHG emissions growth is similar with oil consumption growth. However, the effect of promoting EV penetration on GHG emissions mitigation is not as significant as oil conservation. With all five measures implemented, 62.2% and 73.4% reduction of life cycle GHG emissions can be achieved in 2030 and 2050. The peak of GHG emissions will appear by around 2040, ten years later than the oil consumption peak.

Fig. 8 presents the comparison among several studies on projection of GHG emissions by China’s passenger vehicles [5, 12, 13]. These results should be compared in different contexts as noted with the figure. Generally, early studies tend to underestimate the future trends.

5.3 Sensitivity analysis

To account for the possible errors resulted by the uncertainty of factors, we conducted a sensitivity analysis for GDP growth rate, FCR reduction rate and EV penetration rate. Fig. 9 presents the effect of factor changes on life cycle GHG emissions by China’s passenger vehicles in 2050. As presented, GHG emissions are most sensitive to GDP growth rate. When changing GDP growth rate within ±5%, GHG emissions in 2050 will change within (−5.6%, 5.9%), implying that projection result of this study is closely related to the GDP growth rate assumption. When changing FCR reduction rate and EV penetration rate within ±5%, GHG emissions in 2050 will change within (−2.3%, 2.3%) and (−1.6%, 1.7%).

Fig. 9. Sensitivity analysis of GDP growth rate, FCR reduction rate and EV penetration rate’s effect on life cycle GHG emissions in 2050.

6. Discussion and conclusive remarks

In 2009, the Chinese government endorsed a goal of GHG emissions mitigation that the GHG emissions intensity (the volume of GHG emissions divided by GDP) should be reduced by 40%–45% in 2020 compared with the 2005 level [43]. If using this goal as cap for passenger vehicle fleet, the total life cycle GHG emissions by passenger vehicle fleet should be lower than 244 million tons in 2020. However, even by implementing all five measures concluded in this study, the GHG emissions by passenger vehicle fleet in 2020 will be as high as 489 million tons. The gap between the goal and the estimated lowest GHG emissions reflects the severe circumstance that China’s private road transport sector faces.

The fuel conservation and GHG emissions mitigation effects of the measures were estimated based on the assumptions in Section 4. If the assumptions for reference scenario and the measures are changed, the effects will be different. Therefore, the scenarios provided by this study should be considered with reference to the assumptions.

In this study, the measures and scenarios were estimated and evaluated in terms of fuel conservation and GHG emissions mitigation effects. However, a wider scope of influences by these measures should be considered when formulating related policies. For example, although the measure of constraining vehicle registration is effective on fuel conservation and GHG emissions mitigation, it is unfavorable to China’s automotive industry and related economy. The best combination of the measures should be based on both fuel consumptions and GHG emissions boundaries and China’s national conditions.

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References


