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# Scenario analysis of energy consumption and greenhouse gas emissions from China's passenger vehicles

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ABSTRACT

To address the energy and environmental concerns over the rapid growing vehicle ownership, China has newly implemented a wide range of mitigation measures over recent years. In this study, the baselines of energy consumption and GHG (greenhouse gas) emissions from China's passenger vehicles are updated by incorporating the impacts from the latest mitigation policies and associated vehicle fleet characteristics changes. The results indicate that GHG emissions from China's passenger vehicles were about 486 mt $CO_2e$ in 2014, accounting for roughly 5% of national total GHG emissions. Under Business-as-Usual scenario, GHG emissions will peak by 2027 at the level of 810 mt $CO_2e$, and then decrease to 650 mt $CO_2e$ in 2050. The currently implemented mitigation measures, with fuel consumption regulation playing the essential role, have effectively offset the impacts from the fast growing passenger vehicle ownership. With all mitigation measures maximizing their impacts, GHG emissions can peak five years earlier at a 15% lower level.



## 1. Introduction

Driven by economic and population growths, global passenger vehicle sales experienced rapid increase over recent years [22]. Among all the countries, China showed the strongest growth, from 1.2 million in 2000 to 19.7 million in 2014, accounting for about 30% of global passenger vehicle sales. However, as the passenger vehicle ownership level in China (86 vehicles/1000 people in 2014) is still very low compared with the levels in developed countries (300–500 vehicles/1000 people), there is still great growth potential in China's passenger vehicle sales.

The fast growing passenger vehicle ownership caused severe concerns over its impacts on energy security, air pollution, and climate change issues [10]. For example, China's dependence on oil import increased from 30% in 2000 to nearly 60% in 2014, mostly due to the fast increase of oil demand from vehicles [20]. According to Ref. [4]; motor vehicles were responsible for 31.1% of PM2.5 emission from local sources, topping any other single sector. As estimated by Ref. [19]; $CO_2$ emissions from road transport accounted for 6.9% of China's total $CO_2$ emissions in 2012. To address these issues, both China's central and local governments have implemented a wide range of mitigation measures, especially over recent years [15].

In the Ref. [13] study conducted in 2011, with 2010 as the base year, several scenarios of energy consumption and GHG (greenhouse gas) emissions from China's passenger vehicles were developed. During the same time period, several other studies also focused on evaluating the energy and environmental impacts from China's passenger vehicles. Ref. [33] estimated the $CO_2$ and pollutant emissions from China's passenger cars based on VKT (vehicle kilometers traveled) and emission factors. Ref. [35] projected the fuel consumption from China's vehicles through 2030 based on the LEAP (Long-range Energy Alternatives Planning) system software. Ref. [9] focused on urban taxis and evaluated the cost effectiveness and environmental benefits of various vehicle technologies. However, as mentioned above, new trends of policy implementation and technology improvements emerged over recent years. Accordingly, vehicle fleet characteristics showed significant changes. Among all the newly implemented and updated policies, the following policies can have substantial impacts on the energy consumption and GHG emissions from passenger vehicles.

(1) The update of fuel consumption regulation. In 2012, China started to implement the phase III fuel consumption

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**Abbreviations**

| | |
|---|---|
| BAU | Business-as-Usual |
| BEV | battery electric vehicle |
| BPV | business passenger vehicle |
| CCS | Carbon Capture and Storage |
| CNG | compressed natural gas |
| CTL | Coal-to-Liquid |
| DV | diesel vehicle |
| EV | electric vehicle |
| FCV | fuel cell vehicle |
| FF | fleet frozen scenario |
| GDP | Gross Domestic Production |
| GHG | greenhouse gas |
| GTL | Gas-to-liquid |
| GV | gasoline vehicle |
| HEV | hybrid electric vehicles |
| ICE | internal combustion engine |
| IEA | International Energy Agency |
| LEAP | Long-range Energy Alternatives Planning |
| MIIT | Ministry of Industry and Information Technology |
| MM | maximum mitigation scenario |
| mt | megaton |
| mtoe | megaton of oil equivalent |
| NEDC | New European Driving Cycle |
| NGV | natural gas vehicle |
| PHEV | plug-in hybrid electric vehicle |
| PPV | private passenger vehicle |
| TX | taxi |
| VKT | vehicle kilometers traveled |

regulation, which aimed to reduce the fleet average fuel consumption rate of new passenger vehicles to 7 L/100 km in 2015 [34]. A more ambitious target of 5 L/100 km was planned to be achieved by 2020 through the implementation of phase IV fuel consumption regulation.

(2) Subsidy scheme to accelerate EV (electric vehicle) market penetration. In 2010 and 2013, China started the phase I and phase II subsidy schemes for EV purchase, which significantly boomed EV sales in China's vehicle market [11]. According to Industry Development Plan for Energy Saving and New Energy Vehicles, the accumulated sales of EVs will reach 5 million in 2020 [28].

(3) Restrictions on vehicle ownership and vehicle use in numerous big cities. Beijing implemented restriction policies on vehicle ownership and vehicle use in 2011 and 2008, respectively, which had a demonstration effect on more cities considering implementing such policies [12]. As of 2014, a total number of 7 and 13 cities have issued similar restriction policies on vehicle ownership and vehicle use, with a considerable number of cities potentially to implement such policies in the near future.

With all the above-mentioned policies underway, the baselines of energy consumption and GHG emissions from China's passenger vehicles have been substantially affected, which can not be reflected in previous literatures. Therefore, it is necessary to re-evaluate the future trend, with all up-to-date policy initiatives and technology improvements considered. With the aim of filling such a gap, a bottom-up accounting framework is established. Based on the accounting framework, a set of scenarios reflecting the possible trajectories of energy consumption and GHG emissions from China's passenger vehicles are developed. The whole paper is organized as follows. The next section describes the research framework and data treatment. Following this, the scenarios are shown. The subsequent section presents discussions and policy implications. The last section concludes the whole study.

## 2. Methods

### 2.1. Overarching framework

As Fig. 1 shows, a bottom-up accounting framework is established to estimate energy consumption and GHG emissions from passenger vehicles. Based on vehicle utilities, passenger vehicles are classified into three categories, namely, PPV (private passenger vehicles), BPV (business passenger vehicles) and TX (taxis). From the vehicle technology perspective, six different vehicle propulsion technologies are considered in the analysis, which will be introduced in the section of technology penetration. Accordingly, vehicle fuel considered in this study include conventional fuels (gasoline, diesel and CNG (compressed natural gas)), their major alternative fuels (bioethanol, coal methanol), and fuels for advanced vehicles (electricity, hydrogen).

Equations (1) and (2) describe the calculation process employed in this study. Energy consumption is decomposed into vehicle sales, survival rate, vehicle use intensity, technology penetration, energy intensity, and alternative fuel uses. GHG emissions are obtained based on energy consumptions and GHG emissions intensities. For the factors that have substantial impacts on energy consumption and GHG emissions from passenger vehicles, such as vehicle sales, vehicle use intensity, etc, multiple scenarios are established for these factors. The scenarios typically include one BAU (Business-as-Usual) scenario and one alternative scenario. Note that the GHG emissions intensity employed in the analysis are based on the life cycle perspective, which implies that the estimations of GHG emissions from passenger vehicles are the life cycle emissions. The timeframe of the scenarios is 2000–2050.

$$EC_{i,r} = \sum_p \sum_q \sum_{i_0 \le j \le i} SA_{j,p} \cdot SR_{j,i,p} \cdot UI_{j,i,p} \cdot TS_{j,p}^{j,p,q} \cdot EI_{j,q} \cdot ES_{i,q}^{i,q,r} \quad (1)$$

$$GE_i = \sum_r EC_{i,r} \cdot GI_{i,r} \quad (2)$$

where, $EC_{i,r}$ is the energy consumption of type $r$ fuel in year $i$ (MJ); $GE_i$ is the GHG emissions in year $i$ (t $CO_2$e); $SA_{j,p}$ is the sales of type $p$ passenger vehicles in year $j$; $SR_{j,i,p}$ is the survival rate of type $p$ passenger vehicles sold in year $j$ at the vehicle age of $i$-$j$; $UI_{j,i,p}$ is the use intensity of type $p$ passenger vehicles sold in year $j$ at the vehicle age of $i$-$j$ (km); $TS_{j,p}^{j,p,q}$ is the share of passenger vehicles with type $q$ propulsion technology out of all type $p$ passenger vehicles sold in year $j$; $EI_{j,q}$ is the energy intensity of passenger vehicles with type $q$ propulsion technology sold in year $j$ (MJ/km); $ES_{i,q}^{i,q,r}$ is the share of energy consumption of type $r$ fuel out of total energy consumption by passenger vehicles with type $q$ propulsion technology in year $i$; $GI_{i,r}$ is the GHG emissions intensity of type $r$ fuel in year $i$ (t $CO_2$e/MJ); $i_0$ is the year from which passenger vehicle sales start to be accounted.

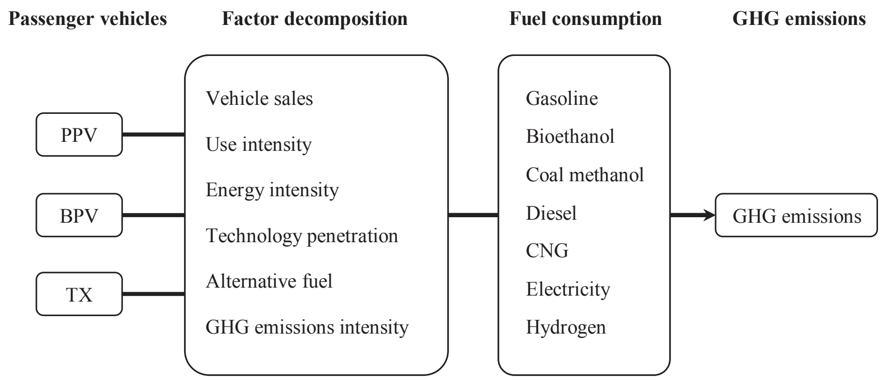


**Fig. 1.** Research framework of this study.

## 2.2. Fleet characteristics

### 2.2.1. Vehicle sales and stock

Total passenger vehicle sales from 1980 to 2014 are determined by referring toRefs. [22] and [13]. The shares of PPVs, BPVs, and TXs out of the total sales are not available in the official statistics. In this study, the shares are estimated by employing a backward induction approach. Specifically, vehicle stock is the function of vehicle sales and survival rate, as equation (3) shows. In other words, given the vehicle stocks and the survival patterns, vehicle sales can be obtained through backward calculation. Vehicle stocks of PPVs, BPVs and TXs are available in the China Statistical Yearbook [20]. Vehicle survival patterns in China's context have been investigated by existing studies [14]. In this study, a logistic function is used to describe the survival pattern, as equation (4) shows. The average lifespan of PPVs, BPVs and TXs are assumed to be 15, 10 and 5 years, respectively. Based on the estimations, the sales of PPVs, BPVs and TXs were 18.2 million, 1.3 million and 0.2 million in 2014, accounting for 92%, 6% and 1% of total passenger vehicle sales, respectively.

$$VS_{i,p} = \sum_{i_0 \le j \le i} SA_{j,p} \cdot SR_{j,i,p} \quad (3)$$

$$SR_{j,i,p} = \frac{1}{1 + e^{\alpha_{j,p} \cdot (i - j - LS_{j,p})}} \quad (4)$$

where, $VS_{i,p}$ is the vehicle stock of type $p$ passenger vehicles in year $i$; $LS_{j,p}$ is the average lifespan of type $p$ passenger vehicles sold in year $j$; $\alpha_{j,p}$ is the characteristics parameter, which determines the vehicle scrappage intensity of type $p$ passenger vehicles sold in year $j$.

Regarding vehicle sales in the future, an elasticity based approach is employed to project PPV sales, which correlates vehicle sales to GDP (Gross Domestic Production) and the elasticity of vehicle sales to GDP, as equation (5) shows.

$$GR_{SA,i} = GR_{GDP,i} \cdot \varepsilon_i \quad (5)$$

where, $GR_{SA,i}$ and $GR_{GDP,i}$ are the growth rates of PPV sales and GDP in year $i$; $\varepsilon_i$ is the elasticity of PPV sales to GDP in year $i$.

Existing literatures suggested that elasticity of vehicle sales to GDP changes with vehicle ownership level [6]. Generally, with vehicle ownership level increasing, the elasticity of vehicle sales to GDP declines. As China's PPV sales is in the process of fast growth, there is significant lag between the actual PPV ownership and 'indicated PPV ownership', which is defined as the equilibrium PPV ownership under a constant PPV sales, estimated as PPV sales multiplied by average lifespan. Therefore, indicated PPV ownership, rather than actual PPV ownership, is employed as the criteria to determine elasticity. China's indicated PPV ownership increased from 0.3 vehicles/1000 people in 1980 to 196 vehicles/1000 people in 2014. Meanwhile, elasticity of vehicle sales to GDP showed a decreasing trend, with average elasticity being 3.8, 3.1 and 1.8 for the PPV ownership ranges of 0–50, 50–100 and 100–200 vehicles/1000 people, respectively. For future projection, it is assumed that elasticity of vehicle sales will continue to decrease along the current trend, as Table 1 shows. On the other hand, many of China's big cities have implemented restrictions on vehicle ownership and use [12], which posed significant impacts on vehicle sales. To reflect the possible impacts from more cities implementing such restrictions, one alternative scenario is developed, under which the elasticity values are assumed to be lower than under BAU scenario. Sales of BPVs and TXs are assumed to continue the current growing trend, increasing linearly to 2.0 million and 0.3 million in 2050, respectively. According to the estimation, under BAU scenario and alternative scenario, total passenger vehicle sales will increase to 37.5 million and 32.8 million in 2050 respectively.

Fig. 2 presents China's passenger vehicle stock from 2000 to 2050. The estimation indicates that total stock will increase from 120 million in 2014 to 550 million in 2050 under BAU scenario, and to 481 million in 2050 under alternative scenario. Accordingly, passenger vehicle ownership will reach 397 vehicles/1000 people and 347 vehicles/1000 people in 2050, comparable to the current level in some developed countries. Both passenger vehicle sales and stock will be dominated by PPVs.

### 2.2.2. Vehicle use

Passenger vehicle use intensity in China has been widely investigated. According to Ref. [16]; the national average use intensities of PPVs, BPVs and TXs changed from 18,500, 24,000 and 74,900 km/year in 2002 to 16,900, 22,000 and 99,200 km/year in

**Table 1**
Elasticity of PPV sales to GDP under BAU and alternative scenarios.

| PPV ownership range | Elasticity | |
|---|---|---|
| | BAU | Alternative |
| 200–250 | 0.75 | 0.50 |
| 250–300 | 0.50 | 0.25 |
| 300–350 | 0.25 | 0.10 |
| 350–400 | 0.10 | 0.05 |
| 400–450 | 0.05 | 0.02 |
| 450–500 | 0.02 | 0.01 |
| 500+ | 0.01 | 0 |

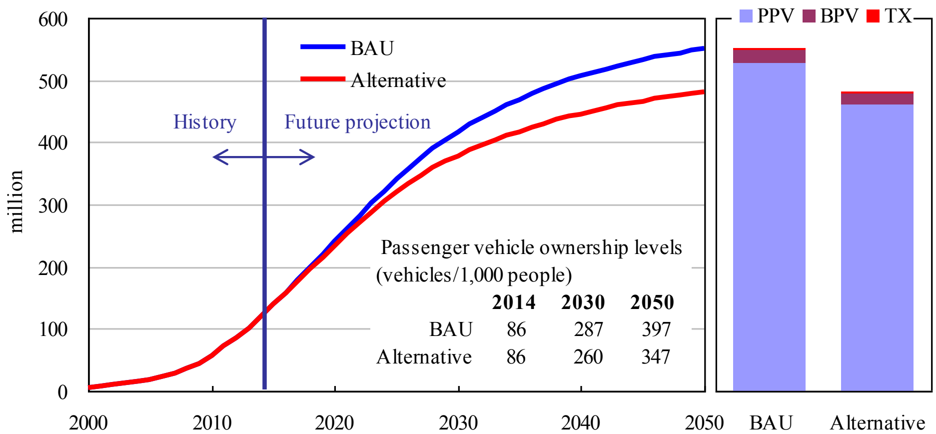


**Fig. 2.** China's passenger vehicle stock and ownership 2000–2050.

2009, respectively. The use intensities of PPVs and BPVs were in downtrends, while TXs in uptrend.

For future projections, it is quite certain that with the mass construction of urban public transport infrastructures and policy incentives for public transport, the use intensity of PPV will continue the current downtrend. However, the extent to which use intensity will decrease is highly uncertain. In this study, one BAU scenario and one alternative scenario of PPV use intensity are established to reflect the uncertainty. Under BAU scenario and the alternative scenario, PPV use intensity will decrease to around 11,000 km/year (about 30 km/day) and 9000 km/year (about 25 km/day) in 2050, respectively. The use intensities of BPVs and TXs are assumed to change to 20,000 km/year and 120,000 km/year in 2020 and stay constant thereafter.

As demonstrated by existing investigations [24], vehicle use intensity declines as vehicle age grows. In this study, an exponential function is employed to describe this process, as equation (6) shows.

$$UI_{j,i,p} = UI_{i,p} \cdot e^{-\beta_p (i-j)} \qquad (6)$$

where, $UI_{i,p}$ is the first-year use intensity of type $p$ passenger vehicles in year $i$ (km); $\beta_p$ is the characteristics parameter, which determines the degradation rate of vehicle use intensity of type $p$ passenger vehicles against vehicle age.

Note that only PPVs are applied with this use intensity degradation process. BPVs and TXs are assumed to maintain constant use intensities throughout the vehicle life. By referring to existing studies [2], the characteristics parameter is assumed to be 0.03 for PPVs.

### 2.2.3. Technology penetration

In this study, passenger vehicles are classified into six technology categories based on their propulsion systems, which are GV (gasoline vehicle), DV (diesel vehicle), NGV (natural gas vehicle), BEV (battery electric vehicle), PHEV (plug-in hybrid electric vehicle) and FCV (fuel cell vehicle)). GVs, DVs and NGVs are all based on ICE (internal combustion engine) technologies. Specifically, GVs and NGVs are normally based on spark ignition ICEs, while DVs on compression ignition ICEs. HEV (Hybrid electric vehicles) are considered as high-efficiency ICE vehicles, thus are covered in the GV, DV and NGV categories. BEVs get energy exclusively from the grid and are powered by the battery-motor propulsion system. PHEVs use both grid electricity and conventional fuels, and can be equivalent to BEVs and HEVs depending on the share of electric drive. FCVs are vehicles powered by fuel cells, with hydrogen as the main fuel.

Historically, China's passenger vehicle market was dominated by GVs, with a market share of around 99%. NGVs were mainly promoted in some natural gas-rich regions like Sichuan province. The market shares of BEV, PHEV and FCV were very low and can be ignored.

The future market penetrations of different vehicle technologies will be affected by technology improvements and policy incentives, and thus can be quite uncertain. In this study, one BAU scenario and one alternative scenario are established to reflect the possible efforts to promote market penetration of advanced vehicle technologies, as Table 2 shows. As BPVs and TXs are normally chosen as the demonstration fleets of advanced vehicle technologies, it is assumed that the market penetration rates of advanced vehicle technologies are higher in BPV and TX fleets.

### 2.2.4. Energy intensity

Energy efficiency improvement of passenger vehicles is mainly driven by fuel economy regulations [5]. China is among the eight countries globally that have implemented fuel economy regulations [23]. China implemented the Phase I, Phase II, and Phase III fuel consumption regulations for passenger vehicles in 2005, 2008 and 2012, respectively. Accordingly, the fleet average fuel consumption rate of new passenger vehicles decreased from 9.11 L/100 km (2.9 MJ/km) in 2002 to 7.33 L/100 km (2.3 MJ/km) in 2013 [31]. The Phase IV fuel consumption regulation for passenger vehicles will be implemented in 2016, which aims to bring down the

**Table 2**
Market penetration rates of different vehicle technologies.

| Scenario | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|
| | | PPV | BPV | TX | PPV | BPV | TX |
| BAU | GV | 80.5% | 76.6% | 61.0% | 60.0% | 52.0% | 20.0% |
| | DV | 1.0% | 1.2% | 2.0% | 2.5% | 3.0% | 5.0% |
| | NGV | 2.5% | 3.0% | 5.0% | 2.5% | 3.0% | 5.0% |
| | BEV | 4.5% | 5.4% | 9.0% | 15.0% | 18.0% | 30.0% |
| | PHEV | 10.5% | 12.6% | 21.0% | 15.0% | 18.0% | 30.0% |
| | FCV | 1.0% | 1.2% | 2.0% | 5.0% | 6.0% | 10.0% |
| Alternative | GV | 61.0% | 52.8% | 20.0% | 20.0% | 16.0% | 0.0% |
| | DV | 2.0% | 2.6% | 5.0% | 5.0% | 4.0% | 0.0% |
| | NGV | 5.0% | 5.0% | 5.0% | 5.0% | 5.0% | 5.0% |
| | BEV | 9.0% | 13.2% | 30.0% | 30.0% | 33.0% | 45.0% |
| | PHEV | 21.0% | 22.8% | 30.0% | 30.0% | 30.0% | 30.0% |
| | FCV | 2.0% | 3.6% | 10.0% | 10.0% | 12.0% | 20.0% |

fleet average fuel consumption rate to 5 L/100 km (1.6 MJ/km) in 2020. As GVs will continue to dominate the passenger vehicle market in the foreseeable future, the near-term regulation targets can basically reflect the fuel consumption improvement trajectory of GVs. Regarding the post-2020 trends, China is likely to further tighten the fuel consumption regulation by following the regulation trajectories of leading regions like EU. As estimated by Ref. [3]; considerable potential exists in reducing fuel consumption rate of passenger vehicles through conventional technology improvements, including engine efficiency improvement, transmission optimization, lightweight design [7], etc. With consistent improvements, fuel consumption rate of GVs can be reduced to as low as around 3 L/100 km. In this study, one BAU scenario and one alternative scenario are established, under which fuel consumption rate of GVs will decrease to 4 L/100 km (1.3 MJ/km) and 3 L/100 km (1.0 MJ/km) in 2030, respectively. The energy intensities of DVs and NGVs are assumed to be 85% and 100% of GVs. The energy intensities of BEVs and FCVs are assumed to be 0.54 MJ/km and 0.74 MJ/km, and do not change over time. Note that all the assumed energy intensities are the NEDC (New European Driving Cycle) normalized energy intensities. The real-world energy intensity is assumed to be 15% higher than the normalized values [36].

### 2.2.5. Alternative fuels

Bioethanol is the major alternative to gasoline [37]. China started to promote bioethanol since around 2002, with aging corn and wheat as the major feedstocks. However, with the expansion of production capacity, the demand for grain as bioethanol feedstock became a threat to food security. Since the end of 2006, grain ethanol productions have been restricted to four major sites, with an annual production of around 1.5 mt (megaton). The second-generation bioethanol, which uses non-grain crops as feedstocks, is being produced in several newly established facilities, with an annual production of around 0.5 mt. As estimated by Ref. [17]; with technology improvement and cost reduction, second-generation bioethanol will lead the growth of bioethanol consumption in the coming decades. In this study, the future consumption of bioethanol is projected by referring to the IEA estimations, i.e., from 0.05 EJ in 2012 to 1.0 EJ in 2050.

As China is rich in coal, coal-derived alternative fuels have been promoted to reduce oil use, with coal methanol as the representative. Under the organizing of the MIIT (Ministry of Industry and Information Technology), the uses of M100 and M85 are being demonstrated in Shanxi, Shaanxi and Shanghai. Besides, several local initiatives are underway to promote the use of low methanol mix fuels. It was estimated that about 4 mt of coal-methanol was consumed as alternative fuel in 2013, and total consumption will reach about 10 mt in 2020 [21]. On the other hand, as the life cycle GHG emissions of coal methanol is significantly higher than gasoline, the use of coal methanol as alternative fuel is likely to be constrained by GHG mitigation considerations. In this study, it is assumed that total coal methanol consumption will reach 10 mt by 2020 and stay constant thereafter.

Other alternative fuels, such as biodiesel, CTL (Coal-to-Liquid), GTL (Gas-to-liquid) are also being promoted to reduce petroleum use. However, these alternative fuels are mostly targeting at diesel replacement, which has little impacts on passenger vehicles. Therefore, only bioethanol and coal methanol are included in the analysis.

### 2.2.6. GHG emissions intensity

Currently, the life cycle GHG emissions intensities of gasoline, diesel and CNG are about 98.9, 102.4, and 73.2 g $CO_2e$/MJ respectively [25]. As the refinery processes of these conventional fuels are quite mature, it is assumed that their emission intensities will not change over time. Considering the emission intensity of bioethanol, most existing estimations were case-based and showed considerable differences [26]. Generally, the emission intensity of grain ethanol is lower than gasoline. Second generation bioethanol shows even lower emission intensities. The emission intensity of coal methanol is currently at a high level of 346 g $CO_2e$/MJ, but shows considerable reduction potential. With CCS (Carbon Capture and Storage) technology applied, the emission intensity of coal methanol can be lowered to 113 g $CO_2e$/MJ in 2030 [25].

As estimated by Ref. [19]; the emission intensity of power generation in China was about 766 g $CO_2$/kWh in 2010, which was higher than most other countries. This can be mostly attributed to the coal dominated power generation structure. On the other hand, improvements of generation efficiency and increasing use of low carbon power are underway [32]. IEA established two scenarios regarding emission intensity of power generation in China, namely, the 4DS (4 Degree Scenario) and 2DS (2 Degree Scenario), which is employed as the major reference [18]. The emission intensity of hydrogen depends critically on its production pathway, which can range from about 170 g $CO_2e$/MJ (coal derived without CCS) to as low as 20 g $CO_2e$/MJ (Solar power-central production) [1]. By referring to the above-mentioned estimations, one BAU scenario and one alternative scenario are established for the emission intensities of vehicle fuels, as presented in Table 3.

## 3. Results

Fig. 3 shows the historical energy consumption and GHG emissions from China's passenger vehicles. Total energy consumption increased from 14 mtoe (megaton of oil equivalent) in 2000 to 113 mtoe in 2014, with an annual growth rate of 16.3%. Gasoline is the dominating vehicle fuel, which accounted for over 95% of total energy consumption in 2014. During the same period, GHG emissions increased from 58 mt $CO_2e$ to 486 mt $CO_2e$, which was responsible for around 5% of China's total GHG emissions in 2014.

In the previous section, the input factors of vehicle sales, vehicle use, energy intensity, technology penetration and emission intensity are assumed with multiple scenarios. Based on these multiple scenarios of input factors, six output scenarios reflecting the possible trajectories of energy consumption and GHG emissions from passenger vehicles are established, as Table 4 shows. Among the six output scenarios, BAU scenario is based on the BAU scenarios of all input factors, which reflects the future trend with all policy and technology factors continuing their current trends. FF (Fleet Frozen) scenario is based on the assumption that all input factors are frozen at the current level. FF scenario is used as a comparison to BAU scenario to evaluate the impacts of currently implemented mitigation measures. MM (Maximum Mitigation) scenario is based on the alternative scenarios of all input factors, which reflects the future trend with all mitigation potentials exploited. Between BAU scenario and MM scenario, four partial

**Table 3**
GHG emissions intensities of different vehicle fuels (Unit: g $CO_2e$/MJ).

| | | Current | 2030 | 2050 |
|---|---|---|---|---|
| BAU | Bioethanol | 115 | 100 | 50 |
| | Coal methanol | 346 | 226 | 113 |
| | Electricity | 213 | 144 | 111 |
| | Hydrogen | 200 | 100 | 20 |
| Alternative | Bioethanol | 115 | 50 | 15 |
| | Coal methanol | 346 | 113 | 113 |
| | Electricity | 213 | 72 | 8 |
| | Hydrogen | 200 | 50 | 10 |

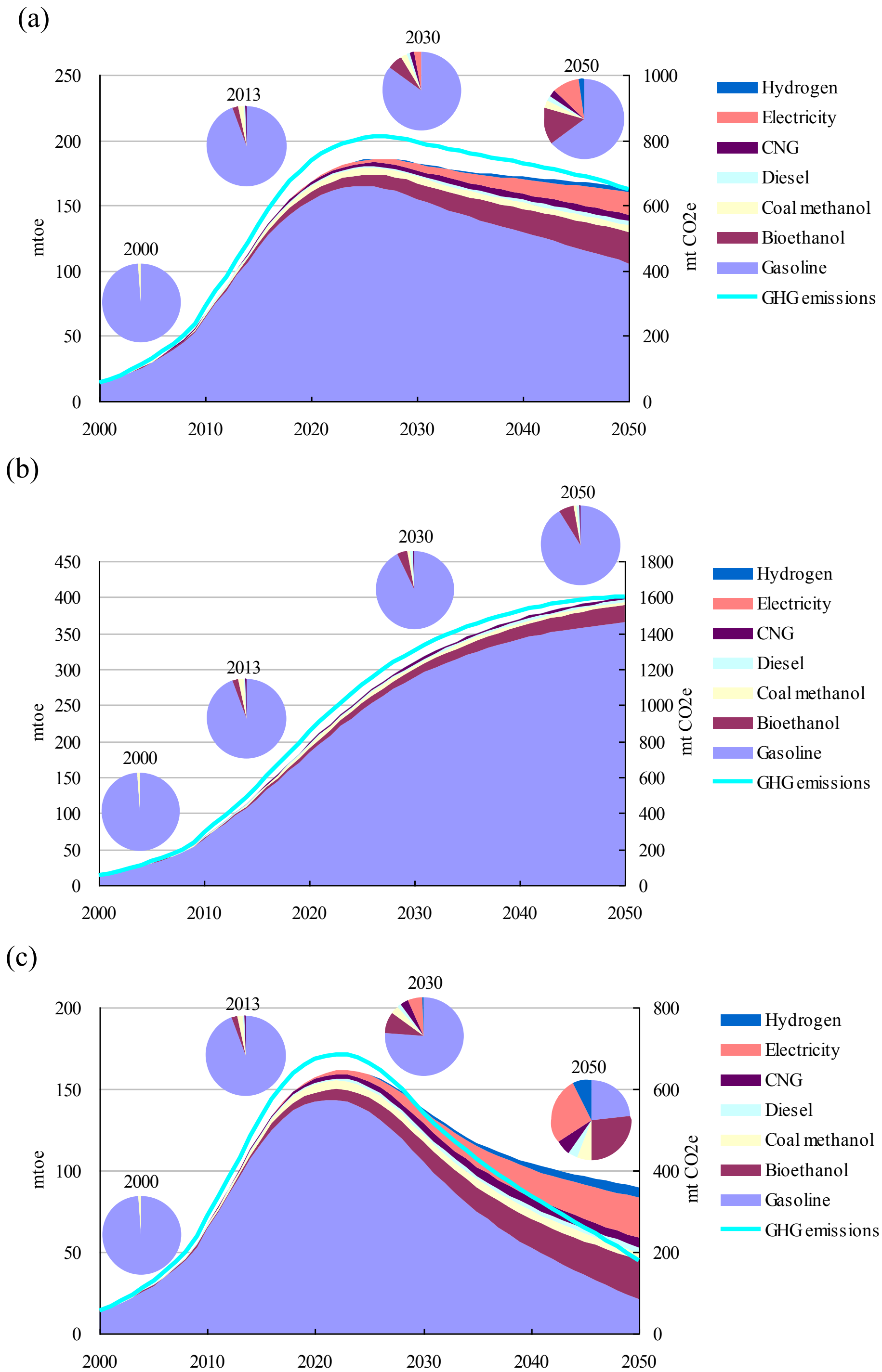


**Fig. 3.** Energy consumption and GHG emissions under (a) BAU scenario (b) FF scenario and (c) MM scenario.

mitigation scenarios named M1, M2, M3 and M4 are established, under which mitigation measures are implemented to different extents. These partial mitigation scenarios are used to estimate the impacts from each single mitigation measure.

### 3.1. BAU scenario

As Fig. 3(a) shows, under BAU scenario, total energy consumption of China's passenger vehicles will increase rapidly in the near future and peak by 2027 at the level of 186 mtoe, which is 65% higher than the 2014 level. After the peaking point, total energy consumption will decrease in a mild pattern and reach 164 mtoe in 2050. The growth trend of GHG emissions is similar to that of energy consumption, which peak by 2027 at the level of 810 mt $CO_2e$. However, benefiting from the decreases of emission intensities of vehicle fuels, GHG emissions after the peaking point show a steeper decrease, reaching 650 mt $CO_2e$ in 2050.

Gasoline will continue to be the dominating vehicle fuel, although its share will decrease from 95% in 2014 to 64% in 2050. The peaking point of gasoline consumption will emerge at 2025, a

**Table 4**
Output scenarios and their major assumptions.

| | Vehicle sales | Vehicle use | Energy intensity | Technology penetration | GHG emissions intensity |
|---|---|---|---|---|---|
| FF | BAU | Frozen | Frozen | Frozen | Frozen |
| BAU | BAU | BAU | BAU | BAU | BAU |
| M1 | Alternative | BAU | BAU | BAU | BAU |
| M2 | Alternative | Alternative | BAU | BAU | BAU |
| M3 | Alternative | Alternative | Alternative | BAU | BAU |
| M4 | Alternative | Alternative | Alternative | Alternative | BAU |
| MM | Alternative | Alternative | Alternative | Alternative | Alternative |

Note: Frozen denotes staying at the level of 2014.

bit earlier than the peaking of total energy consumption. Peaking gasoline consumption will be 164 mtoe, which is 54% higher than the 2014 level. Bioethanol and coal methanol show considerable potentials of gasoline replacement, which will account for 15% and 3% of total energy consumption in 2050, respectively. The consumptions of diesel, CNG and hydrogen are very low due to the limited market penetration potentials of DVs, NGVs and FCVs under BAU scenario. Electricity consumption shows great growth potential, which will account for 10% of total energy consumption in 2050.

Considering the breakdown of energy consumption by vehicle utilities, PPVs are responsible for the major part of total energy consumption and GHG emissions. Although the vehicle stocks of BPVs and TXs are far lower than that of PPVs, they are used in a much higher intensity than PPVs, which makes their energy consumptions and GHG emissions not ignorable. In 2050, BPVs and TXs will contribute to 7% and 3% of total energy consumption.

### 3.2. FF scenario

As Fig. 3(b) shows, total energy consumption and GHG emissions under FF scenario will keep an increasing trend through 2050, with no sign of saturation emerging. Total energy consumption and GHG emissions will be 400 mtoe and 1606 mt $CO_2$e in 2050, which are 3.5 times and 3.3 times the 2014 levels. Compared with BAU scenario, FF scenario shows an uncontrolled growth pattern due to the lack of mitigation efforts. In other words, existing mitigation policies and technology improvements are quite necessary in avoiding a future like under the FF scenario.

### 3.3. MM scenario

As Fig. 3(c) shows, total energy consumption under MM scenario will peak by 2023 at the level of 162 mtoe, and decrease to 90 mtoe in 2050. Accordingly, GHG emissions will peak by 2022 at the level of 685 mt $CO_2$e, and decrease to 180 mt $CO_2$e in 2050, which is similar to the level in 2007. Compared with BAU scenario, both the peaking points of energy consumption and GHG emissions emerge around five years earlier. The peaking levels of energy consumption and GHG emissions are 13% and 15% lower than under the BAU scenario. Besides, the mix of energy consumption changes significantly, with alternative fuels and advanced fuels gaining higher shares. The share of gasoline use out of total energy consumption will decline to 23% in 2050.

The contributions from the mitigation measures can be observed by comparing BAU scenario with M1, M2, M3, M4 and MM scenarios. As Fig. 4 shows, the mitigation measures of vehicle sales restriction (BAU vs. M1), vehicle use reduction (M1 vs. M2), energy efficiency improvement (M2 vs. M3), promoting market penetration of advanced vehicle technologies (M3 vs. M4), and reducing emission intensity of vehicles fuels (M4 vs. MM) contribute to 17%, 21%, 19%, 6% and 36% of total GHG emissions reduction, respectively. It should be noted that promoting market penetration of advanced vehicle technologies alone can only have limited impacts on GHG emissions, because the mitigation potentials of advanced vehicle technologies depends critically on the emission intensities of electricity and hydrogen fuels. Only when promoting BEV and FCV is coupled with low emission electricity and hydrogen, can a deep cut of GHG emissions be achieved, as the comparison between M3 scenario and MM scenario demonstrates.

## 4. Discussions and policy implications

By comparing estimations in this study with previous studies, it turns out that this study reveals a much more optimistic BAU scenario. This can be mostly attributed to the policy instruments and technology improvements newly emerging, and the associated positive changes in fleet characteristics over recent years. Meanwhile, the mitigation potential revealed by this study is generally higher than previous studies, because of the assumed implementation of more aggressive mitigation measures.

Under BAU scenario, total GHG emissions peak before 2030, which is in line with China's commitment that national GHG emissions peak by around 2030 [30]. In other words, the mitigation policies currently implemented basically guarantee the realization of national mitigation target from the passenger vehicle sector perspective. Despite of the continuous growth of vehicle sales and stock in the coming decades, the early peaking of GHG emissions should be mostly attributed to the stringent fuel consumption regulation currently implemented and the aggressive target of 5 L/100 km by 2020. Under the regulation, the decrease of fleet average fuel consumption rate is fast enough to offset the impact from increasing vehicle sales and stock.

However, as demonstrated by the MM scenario, further deep cuts of energy consumption and GHG emissions, as well as earlier peaking of GHG emissions at a lower level are possible. This needs joint efforts from the government, automotive industry, and the energy sector. From the government perspective, more aggressive mitigation measures need to be implemented. Infrastructures for public transport and non-motorized transport such as urban rail, bus lane and bike lane should be constructed to stimulate the shift from vehicle travel to non-vehicle modes. Fuel consumption regulation should be further tightened beyond 2020 by keeping up with the trajectory of leading regions. Incentives should be initiated to promote the market penetration of advanced vehicles and production of low carbon fuels. From the industry perspective, automotive manufacturers need to facilitate vehicle technology improvement and cost reduction to increase the market competitiveness of advanced vehicles. The energy sector should make efforts on reducing emission intensities of power generation and hydrogen production, to ensure the mitigation capacity of BEVs and FCVs [29].

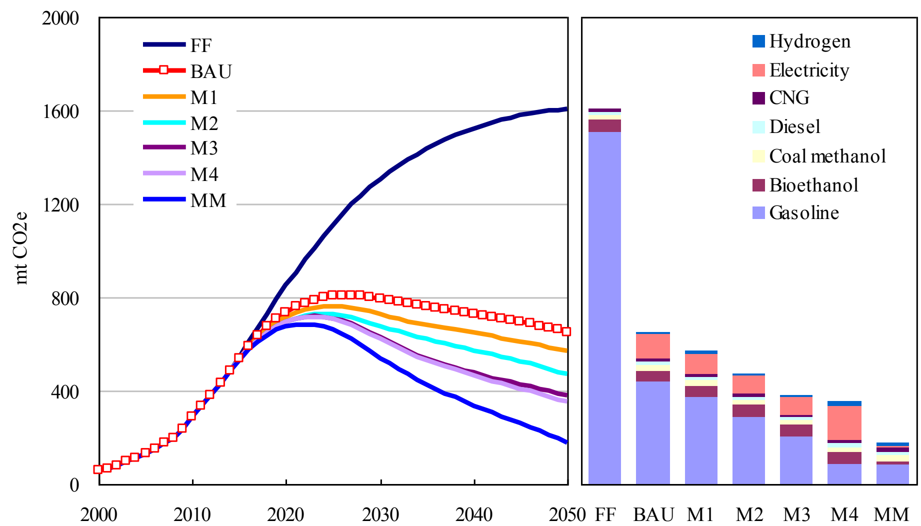


**Fig. 4.** GHG emissions from China's passenger vehicles under different scenarios.

## 5. Conclusions

In this study, by establishing a bottom-up accounting framework, a set of scenarios reflecting the energy consumption and GHG emissions from China's passenger vehicles through 2050 are developed. This study indicates that driven by vehicle sales growth, energy consumption and GHG emissions from China's passenger vehicles experienced rapid growth over recent years, reaching 113 mtoe and 486 mt $CO_2e$ in 2014, which roughly accounted for 5% of China's total GHG emissions in 2014. Under BAU scenario, energy consumption will continue to grow in the next decade, peaking at the level of 186 mtoe in 2027, and then decrease to 164 mtoe in 2050. Gasoline will continue to be the dominating vehicle fuel, with the use of alternative fuels and advanced fuels growing considerably. From the perspective of vehicle utility, PPVs are responsible for over 90% of total energy consumption and GHG emissions. GHG emissions will peak at the level of 810 mt $CO_2e$ in 2027, and decrease to 650 mt $CO_2e$ in 2050. Under MM scenario, the peaking points of energy consumption and GHG emissions emerge earlier at lower levels compared with under BAU scenario. GHG emissions will decrease to 180 mt $CO_2e$ in 2050, which is similar to the level in 2007. This study suggests that the currently implemented policy instruments and undergoing technology improvements can basically guarantee the realization of GHG emissions peaking before 2030. However, to exploit full mitigation potential, more aggressive mitigation measures have to be implemented, which needs joint efforts from the government, automotive industry and the energy sector.

One major gap in this study and most other studies in this research field is the lack of cost analysis. Normally, higher mitigation potential comes with higher mitigation costs. Without the considerations of mitigation costs, the estimations of mitigation potential could be quite misleading, as some mitigation measures are not feasible from the cost effectiveness perspective [27]. Besides, the priorities of mitigation measures can not be well analyzed without cost estimations. Existing studies have explored the cost effectiveness of a wide range of mitigation measures, including mitigation measures in the transport sector [8]. In further studies, these cost estimations could be incorporated into the scenarios and integrated with energy and GHG analysis to present more comprehensive evaluations.

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