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How will greenhouse gas emissions from motor vehicles be constrained in China around 2030?

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HIGHLIGHTS

- We build a projection model to predict vehicular GHG emissions on provincial basis.
- Fuel efficiency gains cannot constrain vehicle GHGs in major southern provinces.
- We propose an integrated policy set through sensitivity analysis of policy options.
- The policy set will peak GHG emissions of 90% provinces and whole China by 2030.

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ABSTRACT

Increasing emissions from road transportation endanger China's objective to reduce national greenhouse gas (GHG) emissions. The unconstrained growth of vehicle GHG emissions are mainly caused by the insufficient improvement of energy efficiency (kilometers traveled per unit energy use) under current policies, which cannot offset the explosion of vehicle activity in China, especially the major southern provinces. More stringent polices are required to decline GHG emissions in these provinces, and thereby help to constrain national total emissions. In this work, we make a provincial-level projection for vehicle growth, energy demand and GHG emissions to evaluate vehicle GHG emission trends under various policy options in China and determine the way to constrain national emissions. Through sensitivity analysis of various single policies, we propose an integrated policy set to assure the objective of peak national vehicle GHG emissions be achieved around 2030. The integrated policy involves decreasing the use of urban light-duty vehicles by 25%, improving fuel economy by 25% by 2035 comparing 2020, and promoting electric vehicles and biofuels. The stringent new policies would allow China to constrain GHG emissions from road transport sector around 2030. This work provides a perspective to understand vehicle GHG emission growth patterns in China's provinces, and proposes a strong policy combination to constrain national GHG emissions, which can support the achievement of peak GHG emissions by 2030 promised by the Chinese government.

1. Introduction

The Chinese government has pledged to peak its greenhouse gas (GHG) emissions around 2030 in the joint announcement with the US in November 2014. In the U.S.-China Joint Announcement on Climate Change, China agreed to peak its CO_2 emissions around 2030 while striving to peak early, and boost the share of non-fossil fuel energy to around 20%. The peak emission goal requires national emissions reach the maximum level around 2030 and start to decrease since then. All GHG emission sectors in China need stringent control, while increasing emissions from

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road transportation endanger the national goal. China has experienced a 23 times increase in the number of vehicles since 1990. Consequently, CO_2 emissions from road transportation in China increased by 7.7 times between 1990 and 2013, while average increase in other economic sectors was only 5 times (Multi-resolution Emission Inventory of China, http://www.meic-model.org). As vehicle sales in China have become the largest in the world, the total vehicle stock is projected to grow fast in next decades [1–3]. The predicted explosive growth of on-road vehicles will consume massive fuel and emit large amount of GHGs. Constraining vehicle GHG emissions will definitely become a big challenge for China.

International experience suggests road transport may be the most difficult sector to reduce GHG emissions. For example, in the EU, transport is the only major sector with rising GHG emissions; and in the US, road transport is experiencing a much slower declining rate for GHG emissions than the other sectors. Since the continued growth of vehicle emissions endangers global or regional climate targets, many studies proposed stringent measures to constrain vehicle emissions [4–6]. Researchers expressed that China could peak its total CO_2 emissions around 2030, while the transport sector may continue the growth [7,8]. Many studies have projected the future energy use and GHG emissions of road transportation in China. They provide valuable information on vehicle stock growth and survival patterns [2,3], future energy use and emission trends [1,9–13], and effects from electric vehicles and alternative fuels [14–23].

These studies are all conducted at the national level. While provincial disparities of China's transport sector are being analyzed more frequently in recent years, very few researches focus on provincial emission projection. Literatures show regional inequity in vehicle growth and fleet turnover patterns is considerable and requires provincial oriented analysis. Using national average parameters for projection may lead to either under- or over-estimation of emissions for different provinces due to uneven regional development [24–27].

Lack of provincial-level emission analysis and projections may lead to poor implementation of national policy. It is particularly important for China to disaggregate the national target into provinces [28–32] to guarantee local efforts are in line with the national goal and track the processes for carbon reduction [33]. It requires the research areas switch from national scale to provincial scale, in order to show a detailed picture for regional disparities and provide better targeted policy suggestions. Previous researches resolve the provincial energy intensities and efficiencies [34–36], the diversity of GHG reduction potentials and costs [37–39] and the benefit of inter-provincial emission trading system [40,41]. However, provincial-specific projection for transport sector is absent. The national total projections cannot help analyze provincial driving forces and allocate national GHG emissions allowance over provinces, which makes it difficult to implement regional oriented policies. A provincial-level study evaluating the development of on-road vehicle GHG emissions towards the national peak and ways of securing their subsequent decline is urgently needed. This work tries to resolve the gap between national GHG target and provincial accountability for reduction efforts in China's transport sector.

In this paper, we project provincial vehicle activity growth in China from 2010 to 2035 and propose strategies to constrain the national total emissions by 2030 and decline the emissions afterwards. We build fleet turnover models for each province to project provincial-level vehicle growth, energy demand and GHG emissions through 2035. Using such model, we evaluate the effects of different policy options and an integrated policy set is finally proposed to ensure peak GHG emissions by 2030. Our objectives are to improve the resolution of vehicle GHG emission projection in China and provide better understanding of the roadmap towards national peak emissions.

2. Methodology and data

2.1. General methodology

Vehicular energy use and GHG emissions are determined by total vehicle numbers, vehicle age distribution, annual distance travelled, fuel consumption rates and carbon intensity of the fuel. Tank-to-wheels (TTW) fuel consumption is calculated at first, and then is multiplied by carbon intensity of the fuel to get TTW GHG emissions. Well-to-wheels (WTW) energy use and GHG emissions are converted from the TTW fuel use on the basis of WTW energy-use intensity and GHG-emission intensity [11]. The reason of WTW analysis is that some polices such as electric cars and biofuel blends transfer emissions from tailpipe to upstream, which requires the whole life cycle analysis to evaluate the total emissions change.

For each province, TTW fuel consumption and GHG emissions are estimated from 2010 to 2035 by Eqs. (1) and (2):

$$Fuel_k = \sum_i \sum_j (VP_i \times X_{i,j,k} \times VKT_{i,j,k} \times FC_{i,j,k} \times density_k) \tag{1}$$

$$Emis_{TTW} = \sum_k (Fuel_k \times EF_k) \tag{2}$$

where i represents vehicle types, including private cars owned by all urban residents (denote as urban PCs) and rural residents (denote as rural PCs), urban motorcycles (urban MCs), rural motorcycles (rural MCs), commercial light-duty vehicles (commercial LDVs), buses, light-duty trucks (LDTs) and heavy-duty trucks (HDTs); j represents vehicle age in years; k represents fuel type; VP_i is the number of vehicles of type i; $X_{i,j,k}$, $VKT_{i,j,k}$ and $FC_{i,j,k}$ represent age distribution (share of vehicles in age class j), annual distance traveled (km) and fuel economy (L km^{-1}) for vehicle type i using fuel k at age j; $density_k$ is the density of fuel k (kg L^{-1}); EF_k is the CO_2 emission factor (g kg^{-1}) (other GHG emissions are ignored in the TTW stage because of their few amount); *Fuel* and $Emis_{TTW}$ are TTW fuel consumption (kg) and CO_2 emissions (g), respectively. Electric motorcycles are excluded from this work because the method of refining spatial resolution of vehicle activity projection from nation to province is not applicable given the fact that the growth functions of electric motorcycles are not clear due to lack of data.

Provincial WTW energy use and GHG emissions are then calculated using Eqs. (3) and (4):

$$Energy_E = \sum_k (Fuel_k \times EI_{k,E}) \tag{3}$$

$$Emis_{WTW} = \sum_k (Fuel_k \times GI_k) \tag{4}$$

where E represents energy source (coal or petroleum); $EI_{k,E}$ represents WTW energy intensity of energy E for fuel k (kg kg^{-1}); GI_k represents WTW GHG emission intensity for fuel k (g kg^{-1}); *Energy* and $Emis_{WTW}$ are WTW energy use (kg) and GHG emissions (g), respectively.

As presented in Eqs. (1)–(4), *VP*, *X*, *EF*, *VKT*, *FC*, *EI* and *GI* are key parameters in this work. *VP* and *X* are modeled for each province using methods described in Section 2.2. TTW CO_2 emission factors, *EF*, are calculated using fuel carbon intensity multiplied by 3.67 (ratio of molecular weight of CO_2 to carbon). National average *VKT* and *FC* are derived from simulation results of the Fuel Economy and Environmental Impact (FEEI) model [42–44], for which the data source and projection method are briefly described

Table 1
Methods to project vehicle stock.

Purpose	Parameter	Description	Data source
$V = V^* \times \exp(\alpha \exp(\beta E))$ (5)			
Model ownership of urban and rural PCs and commercial LDVs; model provincial growth patterns for LDTs and HDTs	V	Vehicle ownership (in numbers per 1000 people)	/
	V^*	Vehicle saturation level (in numbers per 1000 people)	Urban PCs: 400; rural PCs: 500; commercial LDVs: 35; Trucks: 5 [2]
	E	Economic indicator, here is per-capita consumption (in RMB at 2010 price)	[58,59][a]
	α and β	Shape parameters (dimensionless)	Regressed from historical data [60]
$V = \begin{cases} V_{2010} + \varphi \times (E - E_{2010}), E \leqslant E_{v\max} \\ V_{2010} + \varphi \times (E_{v\max} - E_{2010}) - \theta \times (E - E_{v\max}), E > E_{v\max} \end{cases}$ (6)			
Modeling ownership of urban and rural motorcycles	V (V_{2010})	Motorcycle ownership (in numbers per 1000 people)	/
	E (E_{2010})	Economic indicator, here is per-capita consumption (in RMB at 2010 price)	[58,59][a]
	E_{vmax}	The per-capita consumption at which V is maximum (in $ at 2010 price)	$1500 at 2010 price
	φ	The growth rate of motorcycle ownership before E_{vmax} (in numbers per 1000 people per $)	Regressed from historical data [60]
	θ	The decline rate of motorcycle ownership after E_{vmax} (in numbers per 1000 people per $)	Regressed from historical data [60]

[a] GDP and population forecast are from [59], and scaled down to provinces with a growth pattern developed by [58]. Urban and rural per-capita consumption of each province are taken from official statistics [60], and projected using its relationship with per-capita GDP.

in Section 2.3. WTW *EI* and *GI* are determined on the basis of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model [45], which is widely used for analysis of life-cycle energy and environmental impacts of vehicles. The GREET model used in this work is parameterized with Chinese data to reflect real conditions. We update fuel consumption rates in GREET with Chinese data (8.8 L/100 km for cars in 2010) to take into account the specific vehicle displacement size in China. Regarding gasoline composition, we use the composition of gasoline used in China, including sulfur content (50 ppm before 2017 and 10 ppm afterwards), carbon content (85.5%), and density (0.732 kg/L). Details of the GREET model configurations and how *EI* and *GI* are calculated are described in our previous work [11].

We use the framework constructed by Eqs. (1)–(4) to determine how to assure the GHG emissions from on-road vehicles peak around 2030 and not beyond. First, GHG emission pathways under current policies are estimated to evaluate whether peak emissions can be constrained by 2030 without any new measures. The gap of non-compliance is analyzed at provincial level. Second, sensitivity analysis for various policy options are conducted to assess the effectiveness of single policy. Finally, the most appropriate policy measures are developed to curb national GHGs and evaluated considering the uncertainties of vehicle stock projections. The scenario design is described in Section 2.4.

2.2. Modeling provincial vehicle stock (VP) and fleet age distribution (X)

Vehicle population of each type (VP_i) is projected based on different driving forces (Table 1) for each province. Urban PCs, rural PCs and commercial LDVs are projected using the Gompertz function (Eq. (5)), which links economic parameters to vehicle ownership [46,47]. Urban and rural motorcycles are projected following the assumption that motorcycle ownership declines when private income reaches a certain level [1] (Eq. (6)), which shows the competition between car and motorcycle purchases. Bus and truck stocks are driven by total demand for road transport of passenger and freight, respectively [9]. The key issues in stock projection are addressed below.

Table 2
Scenario design.

Scenario[a]	Descriptions[b]
FP	VKT comes from the FEEI model [44]. Fuel economy standards, electrification and fuel blending ratios remain the same level as 2012
CP	VKT comes from the FEEI model [44]. Fuel economy standards of the 4th stage for LDVs and the 1st stage for buses and HDTs are considered. Electrification and fuel blending ratios are projected according to government plans and available literatures
VKT_1	On the basis of CP, reduce the VKT of urban PCs and commercial LDVs by 25% in 2035 comparing 2020
VKT_2	On the basis of CP, reduce the VKT of urban PCs and commercial LDVs by 50% in 2035 comparing 2020
FC_1	On the basis of CP, improve FC by 25% in 2035 comparing the last stage fuel economy standard
FC_2	On the basis of CP, improve FC by 50% in 2035 comparing the last stage fuel economy standard
EV	On the basis of CP, the electrification ratios are doubled
FuelBlend	On the basis of CP, the fuel blending ratios are increased by about 50%
NP	Combine the policies in VKT_1, FC_1, EV and FuelBlend scenarios

[a] Detailed parameters adopted in each scenario are presented in Tables A.1–A.5.
[b] The increment and decrement of all factors are assumed linear in the scenarios.

Provincial Gompertz functions are constructed using historical data of each province. We see very different Gompertz functions among provinces, which illustrates the various growth patterns. Saturation level (V^*) is a key parameter in the use of Gompertz function. For China, values for V^* of 400–600 cars per 1000 people are commonly used [1–23]. V^* is affected by factors such as population density and urban development pattern [2]. The limited space available for driving and parking in urban areas leads to lower V^* than in rural areas. In addition, the government policy of restricting car purchases (e.g., in Beijing, Shanghai, and Guangzhou) also contains vehicle growth in urban area. Therefore, we assume the V^* of urban PCs is 400 and that of rural PCs is 500. For Beijing and Shanghai, the V^* of urban PCs is assumed to be 250 because of their greater willingness to control vehicle stock, and referring to similar growth patterns in other Asian megacities (e.g., Tokyo and Osaka in Japan). The V^* of commercial LDVs is determined as our previous work [2].

Unlike private car stocks, which grow to a saturation level and remain constant, motorcycle ownership decreases linearly beyond a certain income level [48]. This is because people tend to replace motorcycles with cars when their income level increases. Based on the analysis of historical data from urban areas in China [48], we find the switching point from MCs to cars is approximately $1500 for per-capita consumption level at 2010 prices [48]. Therefore, we assume that motorcycle ownership increases before this point and declines after.

Bus and truck growth is driven by traffic volume of road transport. According to China's official forecasts [49], the freight volume by road transport will be 2.4 times its current size around 2030, and the passenger volume will be 3.2 times. The projection is conducted on the basis of economic driving forces, social development requirements and construction plan of road infrastructure [49]. We adopt such projections as total constraints for the whole China and develop provincial growth patterns of bus and truck stocks using Gompertz functions [1,2].

After the total vehicle number is projected, vehicle sales are estimated using a back-calculation method [1,25]. Provincial-level age distribution (X) is then simulated using sales data and survival functions [25]. The survival function is constructed for each province on the basis of historical data. Please refer to our previous work [1,25] for more details.

2.3. National average mileage of single vehicle (VKT) and fuel consumption rate (FC)

In the FEEI model, the *VKT* of model years between 2002 and 2009 come from survey data in China, and future *VKT* is projected on the basis of national travel patterns [44]. The *VKT* of cars is projected to gradually decline, while those of buses and trucks are expected to increase. In addition, *VKT* decline with vehicle age is considered in the FEEI model, and adopted in this work.

The *FC* data are derived from the fuel consumption database for real driving patterns established in the FEEI model [42,43]. It includes the 1st to 3rd stage fuel economy standards for LDVs and the 1st stage standard for LDTs in China. We update the FEEI model with the latest standards published in 2014, including the 4th stage standard for LDVs and the 1st stage standard for buses and HDTs. The former one comes into effect in 2017 and aims to improve fuel economy of new cars to 5 L 100 km^{-1} in 2020, and the latter one takes effect in 2015 and is intended to improve fuel economy of new buses and HDTs by 10–15% comparing present levels. Besides the standards, the FEEI model assumes *FC* decreases annually with technology improvements (0.5% for LDVs and LDTs and 1.0% for buses and HDTs) [11].

2.4. Scenario design

Nine scenarios are designed in this work (Table 2), including "frozen policy" (FP), "current policy" (CP), six scenarios for policy sensitivity analysis (VKT_1, VKT_2, FC_1, FC_2, EV and FuelBlend) and a "new policy" scenario (NP). The policy options considered in the above scenarios are the most widely proposed measures to address energy and environmental issues of road transport in China at present, which include four aspects: strengthening fuel consumption standards, limiting car use intensity, promoting electric vehicles, and blending alternative fuels.

The FP scenario assumes that policies do not change or update and the current situation will persist in the future. The CP scenario describes GHG emission trends under near-term enacted policies (e.g., the 4th stage fuel economy standard for LDVs) (see Section 3.2). Determinants of GHG emission trends in the CP scenario are analyzed at the provincial level (see Section 3.3). We further conduct policy sensitivity analysis (VKT_1, VKT_2, FC_1, FC_2, EV

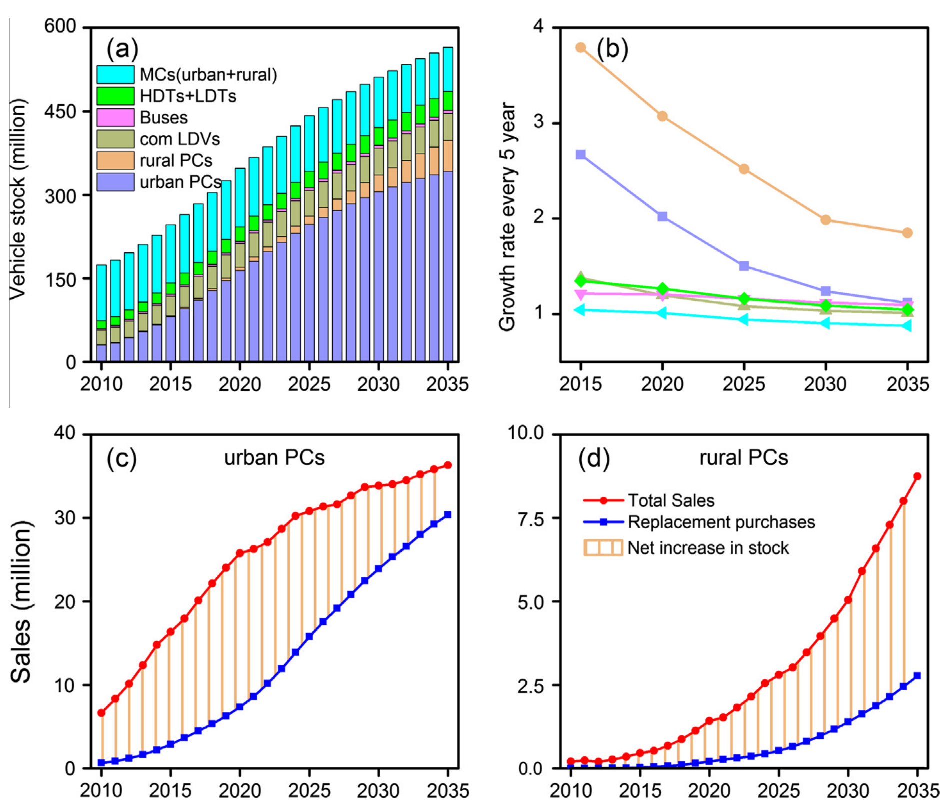

Fig. 1. Vehicle projections from 2010 to 2035: (a) national total stock; (b) growth rate every 5 year (e.g., 2015/2010); (c) sales of urban PCs and the proportion of replacement purchases; (d) sales of rural PCs and the proportion of replacement purchases. Replacement purchases mean that to buy a new car replaces the old car one owns before.

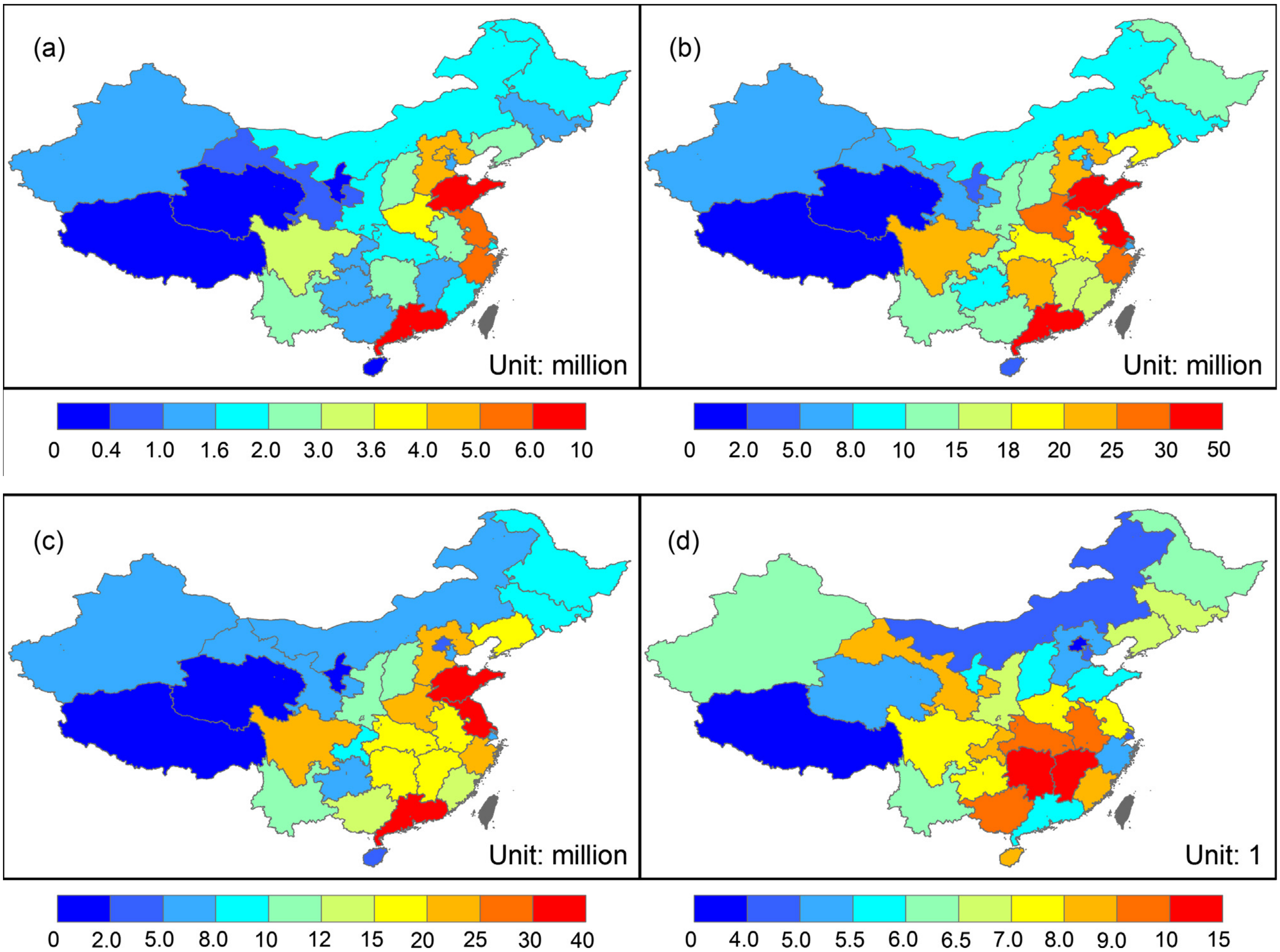

Fig. 2. Provincial vehicle projections from 2010 to 2035: (a) total vehicle stock in 2010; (b) total vehicle stock in 2035; (c) vehicle growth from 2010 to 2035; (d) the ratio of vehicle stock in 2035 to that in 2010. Note: urban and rural MCs are excluded.

and FuelBlend) to determine to what extent the policies should be strengthened to achieve the peak goal, and finally we develop an effective NP scenario (see Section 3.4). Through the nine scenarios, we try to present a complete roadmap towards the peak and ways of securing subsequent decline of vehicle GHG emissions in China.

3. Results

3.1. Total vehicle stock from 2010 to 2035

We project total vehicle stock in China will increase from 174 million in 2010 to 565 million in 2035, as shown in Fig. 1a. All vehicle classes except motorcycles are expected to grow quickly. Urban and rural PCs are projected to increase by up to more than 10 times, and other vehicle stocks are predicted to be doubled. Motorcycles will gradually be replaced by private cars and will decrease by 20% in 2035. Urban and rural PCs are the main drivers of total stock growth, and will contribute 61% and 10% to total vehicle stocks in 2035, respectively. The total stock of rural PCs is one- sixtieth that of urban PCs in 2010, whereas the ratio increases to one-sixth in 2035, because the growth rate of rural PCs is 1.65 times to urban PCs, which can be attributed to its larger fraction of new-growth purchases (Fig. 1d) compared with urban PCs (Fig. 1c). Although the total stock increases, the growth rate gradually declines (Fig. 1b), as economic growth in China slows and private car ownership approaches saturation.

The provinces in China have different vehicle growth patterns as illustrated in Fig. 2. Southern provinces have much higher vehicle growth from 2010 to 2035 than northern and western provinces. This is because the vehicle growth in southern provinces is more sensitive to economic growth than northern provinces. For example, Jilin and Hunan are typical northern and southern provinces, respectively. When their per-capita consumption level increased by 2 times from 2002 to 2010, the urban PCs per 1000 people increased by 20 times in Jilin, while by 25 times in Hunan. The major southern provinces lie in the rapid growth stage for vehicle stock, which promotes significant vehicle growth in the next 20 years. The geographic disparity of vehicle growth highlights the importance of provincial analysis, which helps to identify the key regions for GHG emission abatement.

3.2. Energy demand and GHG emissions under current policies

Fig. 3 illustrates TTW and WTW energy use under FP and CP scenarios. The FP scenario predicts a continuous growth in energy demand, while the energy use under the CP scenario tends to stabilize after 2020. The forthcoming fuel economy standards considered in the CP scenario tighten fuel consumption rates of LDVs and HDTs, the two largest energy consumers. For example, LDVs and HDTs decrease WTW energy use by 34% and 11%, respectively in 2035 in the CP scenario comparing the FP scenario. Consequently, the TTW and WTW energy use in 2035 are 21% and 20% lower in the CP scenario comparing the FP scenario. The cumulative saving of TTW and WTW energy use can reach 47.4 and 60.6 thousand PJ from 2010 to 2035, respectively, or about 5.3–5.6 times the total vehicle energy use in 2010. Though vehicle

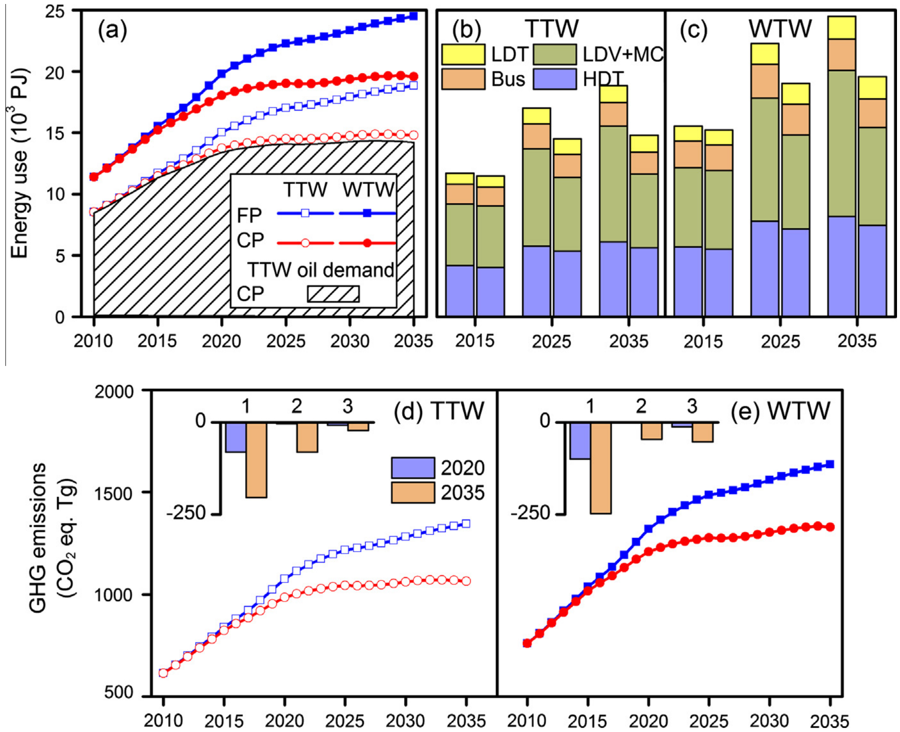

Fig. 3. TTW and WTW energy use and GHG emissions under FP and CP scenarios. Note: LDVs include urban PCs, rural PCs and commercial LDVs; MCs include urban MCs and rural MCs. A difference in 2020 (blue) and 2035 (orange) is decomposed in the inset, into fuel economy improvement (1), electrification (2) and fuel blending (3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energy use could be significantly saved, it is difficult to reverse the growth trend without any new measures, which leads to continued growth of GHG emissions.

Projected annual TTW and WTW GHG emissions under the FP and CP scenarios are presented in Fig. 3d and e. From 2010 to 2035, the TTW and WTW GHG emissions in the CP scenario increase by 75%, while in the FP scenario they increase by about 115%. The largest contribution to GHG reduction in the CP scenario comes from fuel economy improvement, while the impacts of electrification and fuel blending are limited because of high carbon intensity of the whole life cycle in the near future [11,17]. With the increase of non-fossil fuel based electricity and cellulosic ethanol, life cycle carbon intensity of electrification and fuel blending improve. Consequently, such two measures contribute larger GHG reduction in 2035; though the effect is still 80% lower than fuel economy improvement due to limited penetration of electric vehicles and biofuel (see Tables A.3 and A.4). On the basis of above discussions, the current and planned policies in the CP scenario can significantly cut GHG emissions, but cannot achieve the stated objective of peak emissions.

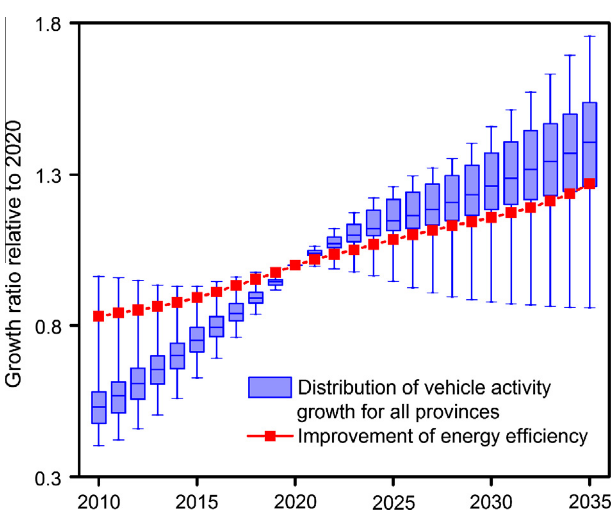

Fig. 4. Provincial vehicle activity growth (the box-whisker plot) and improvement of energy efficiency (the red line) comparing 2020. The three lines of each box from top to bottom represent upper, middle and lower quartiles, respectively. The range of whisker is from the minimum to maximum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Determinants of GHG emissions: provincial analysis

Energy efficiency (kilometers traveled per unit energy use) and vehicle activity (total vehicle kilometers traveled) are key parameters to determine on-road vehicle GHG emissions [50,51]. Vehicle energy efficiency can be considered similar nationwide because of simultaneously implemented fuel economy policies, while vehicle activity growth is subject to significant geographic disparity as discussed in Section 3.1. In some provinces, like Shanghai and Guangdong, GHG emissions growth from vehicles driven by vehicle activity growth can be entirely offset by energy efficiency improvement. In provinces like Jiangxi and Jiangsu, energy efficiency improvements can only partly temper the emission growth driven by vehicle activity growth. Fig. 4 compares provincial vehicle activity growth with national improvement of WTW energy efficiency in the CP scenario. It suggests the energy efficiency improvement can only curb activity growth in less than 25% provinces, while most provinces are not constrained. Developed provinces, such as Guangdong, Shanghai and Beijing, have constrained emissions after 2020 because their vehicle stock approaches saturation and vehicle activity growth slows. The other provinces, major southern provinces such as Jiangxi, Sichuan and Jiangsu, continue vehicle

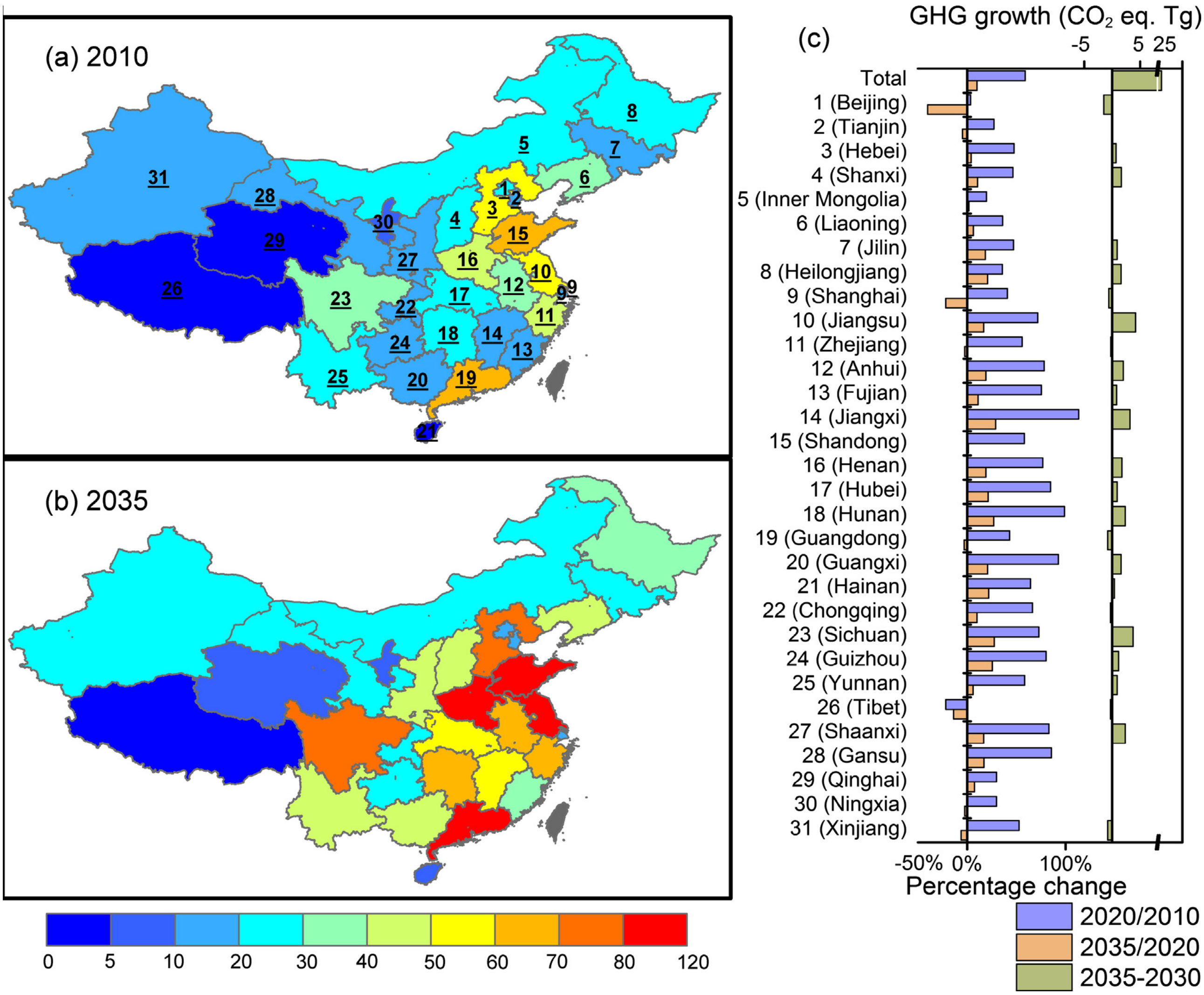

Fig. 5. Provincial WTW GHG emissions in CP scenario: (a) 2010 emissions; (b) 2035 emissions; (c) the growth from 2010 to 2035.

activity growth; they dominate the growth of national GHG emissions and are responsible for the non-compliance with peak emissions.

We evaluate provincial WTW GHG emissions in the CP scenario. The results are shown in Fig. 5. Significant differences exist between provinces for both spatial distribution and growth patterns. In 2010, provinces on the east coast contribute to vehicular GHG emissions most significantly, with the nine provinces being responsible for 45% of the nation's GHG emissions. In 2030, the activity growth in these provinces is almost saturated and entirely offset by improved energy efficiency, therefore the GHG growth falls to zero, or even becomes negative. Many of these provinces will decline GHG emissions since 2030. In 2035, the proportion of GHG emissions from these nine provinces decreases to 39% of the national vehicular GHG emissions. Much faster growth of GHG emissions occurs in major southern provinces, where the energy efficiency improvement cannot offset the dramatic growth of vehicle activity. The objective of new policies should be set to constrain the GHG emissions in the southern provinces.

3.4. Constrain national GHG emissions by 2030

As discussed above, staying at no more than current levels or even with enacted measures ("frozen policy" or "current policy" scenarios) will not constrain the vehicle GHG emissions by 2030, and stricter measures are thus needed. Measures to reduce vehicle GHG emissions can be broadly divided into two categories: reducing vehicle activity and improving energy efficiency. The two measures are accepted by Chinese government not only because of the energy and climate issues but also for urban air pollution problems. To constrain vehicle activity, the Chinese government tries to vigorously develop the public transport system and promote green travel to reduce dependence on cars in urban areas. According to the government plan [52], China plans to increase the share of public transport to 60% in urban areas with more than 1 million residents and increase the share of walking and bicycling by 5–10% in 2017, which should help reduce the VKT of urban cars. However, due to lack of clear action plan until now, we do not include this policy in the analysis of CP scenario to avoid being over optimistic. Such measures will be explicitly designed in the rigorous policy package. To improve energy efficiency, China plans to update fuel economy standards to catch up with the level of other developed countries in 2030, improve market penetration of electric vehicles [53], and increase the proportion of biofuel blends [54]. Stringent fuel economy standards save fuel for the same mileage travelled, and biofuels and electricity could benefit the whole life cycle energy efficiency with the improvement of energy intensity in the fuel production process. To what extent these policies can curb national GHG emissions is evaluated separately as below.

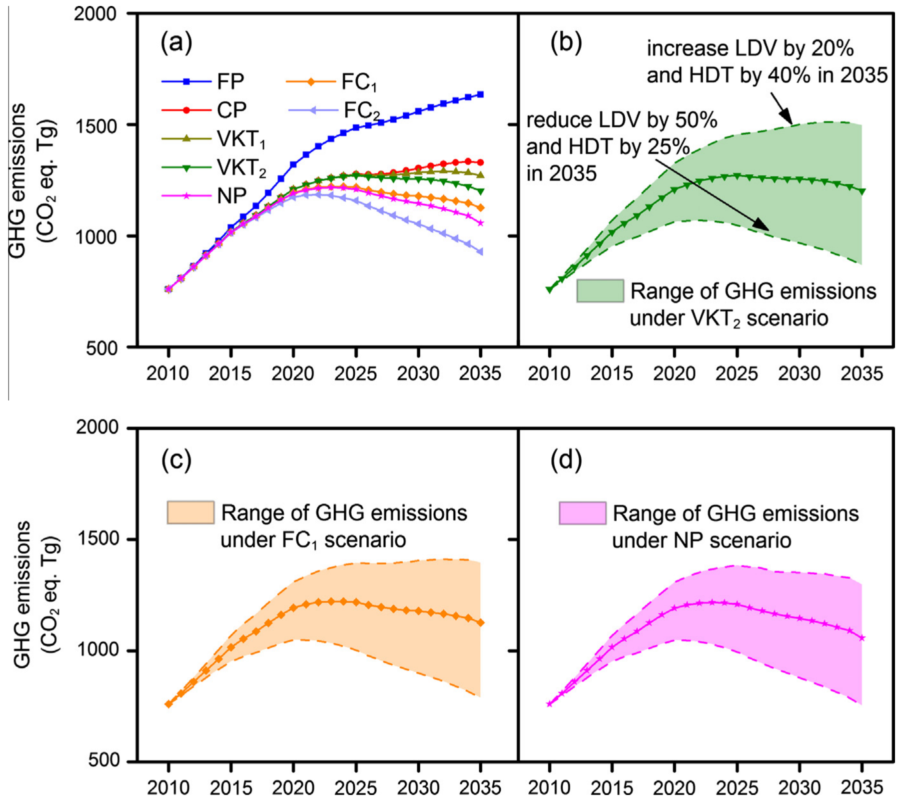

Fig. 6. WTW GHG emissions in various scenarios (see Table 2) (a) and emission ranges of scenario (b) VKT_2, (c) FC_1 and (d) NP. Note: the emissions of FuelBlend and EV are very close to CP and thereby not presented.

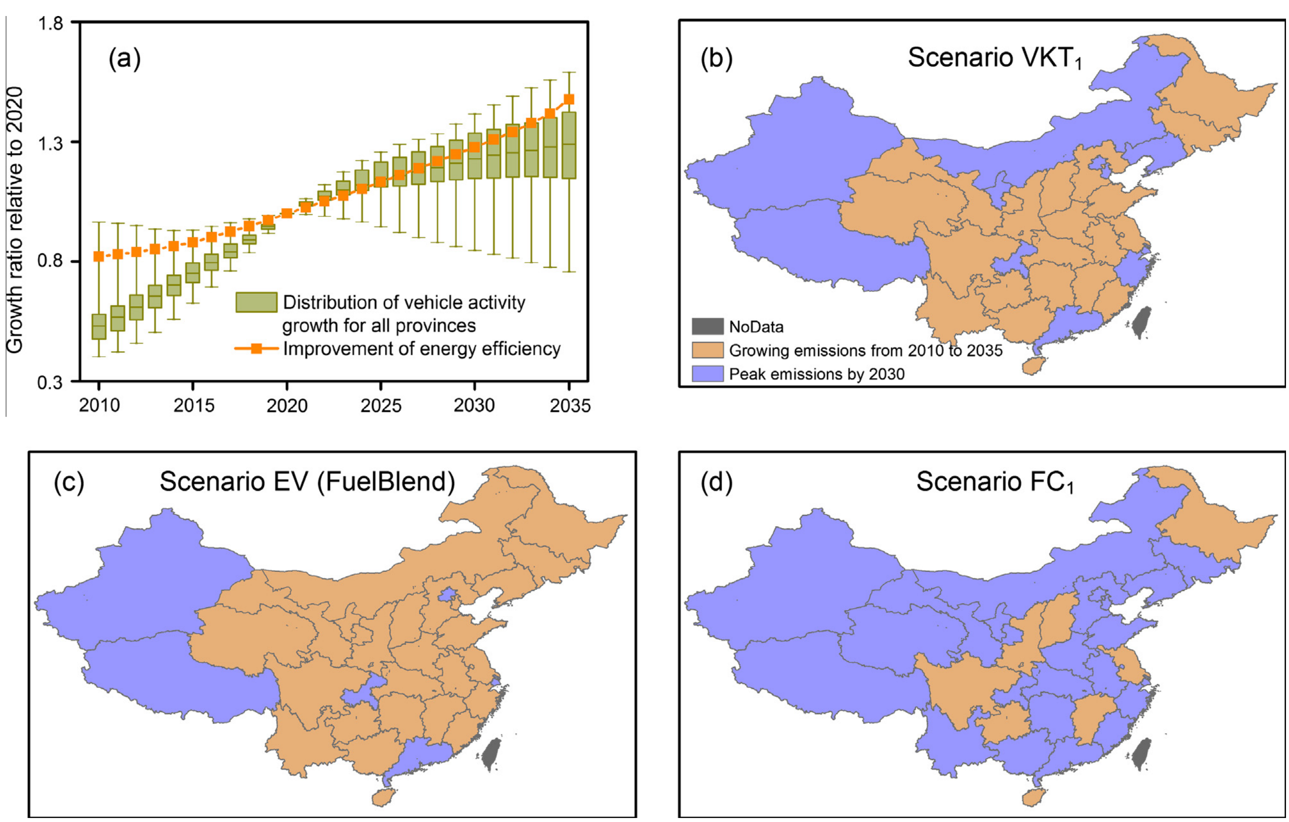

Fig. 7. (a) Provincial vehicle activity growth (the box-whisker plot) and improvement of energy efficiency (the brown line) in the NP scenario. And the provinces have peak GHG emissions by 2030 under (b) VKT_1, (c) EV (FuelBlend) and (d) FC_1 scenarios individually. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table A.1
Projected fuel consumption rates for new vehicles (L 100 km^{-1}) in different scenarios.

	FP[c]				CP				FC_1 (NP)				FC_2			
	2010	2015	2025	2035	2010	2015	2025	2035	2010	2015	2025	2035	2010	2015	2025	2035
LDV-G[a]	8.8	7.9	7.5	7.2	8.8	7.9	5.6	5.3	8.8	7.9	5.2	4.0	8.8	7.9	4.8	2.9
Bus-D[b]	25.8	24.5	22.2	20.1	25.8	22.7	20.5	18.6	25.8	22.7	18.7	14.7	25.8	22.7	17	11.3
LDT-D[b]	12.1	11.8	11.2	10.7	12.1	11.8	11.2	10.7	12.1	11.5	10.3	9.1	12.1	10.9	8.5	6.1
HDT-D[b]	24.9	23.7	21.4	19.4	24.9	21.9	19.8	18.0	24.9	21.9	18.1	14.2	24.9	21.9	16.4	11.0

[a] LDV = urban PC + rural PC + commercial LDV. G means gasoline vehicles and D means diesel.
[b] Fuel consumption rates of gasoline LDT, HDT and bus are 20% higher than diesel ones according to current requirements in China.
[c] Fuel consumption rate of motorcycles is assumed to remain 2.5 L 100 km^{-1} in all scenarios.

Table A.2
Projected VKT for new vehicles (1000 km) in different scenarios.

	FP (CP)				VKT_1 (NP)				VKT_2			
	2010	2015	2025	2035	2010	2015	2025	2035	2010	2015	2025	2035
Urban PC	16.5	14.2	9.9	9.6	16.5	14.2	9.7	7.2	16.5	14.2	9.3	4.8
Rural PC	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
Commercial LDV	16.5	15.5	12.5	12.4	16.5	15.5	12.3	9.3	16.5	15.5	11.8	6.2
Bus	124.0	127.7	131.9	108.0	124.0	127.7	131.9	108.0	124.0	127.7	131.9	108.0
LDT	30.0	31.5	34	35.5	30.0	31.5	34	35.5	30.0	31.5	34	35.5
HDT	80.0	83.3	88.7	92	80.0	83.3	88.7	92	80.0	83.3	88.7	92
MC[a]	5.9	5.1	3.5	3.4	5.9	5.1	3.5	3.4	5.9	5.1	3.5	3.4

[a] MC = urban MC + rural MC.

Fig. 6a presents national WTW GHG emission pathways under different policy options. The single policy of VKT_2, FC_1 and FC_2 can achieve peak GHG emissions by 2030, while the policies of VKT_1, EV and FuelBlend cannot. The VKT_1 scenario is not effective because LDVs only contribute less than 30% emissions around 2030; therefore a small reduction of LDVs' use intensity does not have significant effect. Promote the use of electric vehicles and biofuels have little influence because of their limited penetrations in the whole fleet in the next two decades (see Tables A.3 and A.4). The policy scenario of FC_2 is most effective, which suggests that if China could improve its fleet average fuel economy to reach the world advanced level in 2030, the GHGs emissions could be constrained and peaked successfully. However, the current fuel economy in China is about 10–40% worse than Japan and Europe, and fuel consumption limitations for buses and trucks lag far behind. We think the scenario of FC_2 is over optimistic and difficult to realize. The other two effective policies of VKT_2 and FC_1 are probably attainable according to China's plans and current status, but may fail to constrain emissions by 2030 with fast vehicle growth patterns (Fig. 6b and c). We vary the projections of LDVs and HDTs according to the ranges reported in literatures [1,2,10,17,55] by 50–120% and 75–140%, respectively. It suggests the upper bound of WTW GHG emissions keep growing from 2010 to 2035 (Fig. 6b and c) under scenarios VKT_2 and FC_1. In conclusion, no single policy option can ensure peak emissions by 2030 in China.

On the basis of above analysis, we design a integrated policy package with combination of the four scenarios of FC_1, VKT_1, EV and FuelBlend (NP scenario in Table 2) to accommodate the explosive growth of vehicle activity in China. The NP scenario can constrain national GHG emissions by 2030 (Fig. 6a) and is strong enough to curb vehicle emission growth under fast growth patterns (Fig. 6d). Fig. 7 presents the effect of the NP policy on provincial GHG emission trends. Fig. 7a shows that the NP policy can significantly constrain vehicle activity growth in 28 provinces, with only 3 provinces located in southern China not constrained. A 25% improvement in fuel economy (scenario FC_1) is the most effective policy, which makes 22 provinces peak their GHG emissions. The other three policies (VKT_1, EV and FuelBlend) together can ensure another 6 provinces achieve peak GHG emissions. Though only 90% provinces can peak their GHG emissions, the national total emissions can still be peaked successfully by 2030, caused by compensation effect between provinces.

Table A.3
Projected shares of electric vehicles in LDVs[a] in different scenarios.

	In replacement purchases[b]			In new purchases[b]			In total stock		
	FP (%)	CP (%)	EV[c] (%)	FP (%)	CP (%)	EV (%)	FP (%)	CP (%)	EV (%)
2010	0	0	0	0	0	0	0	0	0
2015	0	1	3	0	1	1	0	0	0
2025	1	6	12	0	3	6	0	2	5
2035	3	28	60	1	14	30	1	13	27

[a] LDV = urban PC + rural PC + commercial LDV.
[b] We assume people are more willing to buy an electric car in their replacement purchases than the first new purchases.
[c] NP scenario is the same as EV scenario for electric vehicle penetration.

4. Discussion

Modeling future energy use and emissions of road transport involve many aspects of assumptions, judgments and parameter estimates with high uncertainty. Though many efforts have been made to reduce uncertainty, we still need to carefully check with boundary conditions of the work and remind the conclusions are highly relevant with such boundaries. In this section, we select several key assumptions in this work, discuss the uncertainties and evaluate their possible influences.

First, we assume the policies would take effect to the extent planned by the government without complete feasibility assessment. We make a careful judgment according to investigation of current situation and different forecasts, but for a rapidly developing country like China, it is not easy to make explicit projections. We believe the designed scenarios present possible future developments under best current understanding, and that they will allow progress to be made before more exact projections are developed.

Second, we build fleet turnover model and estimate vehicle activity for each province, while the other parameters such as VKT and FC remain the same for the whole country. Inventories

Table A.4
Projected biofuel blending ratios in different scenarios.

	FP[a]		CP[b]		FuelBlend (NP)[c]	
	Bio-ethanol (%)	Bio-diesel (%)	Bio-ethanol (%)	Bio-diesel (%)	Bio-ethanol (%)	Bio-diesel (%)
2010	2.5	0.3	2.5	0.3	2.5	0.3
2015	2.5	0.3	3.4	0.7	3.4	0.7
2025	2.5	0.3	7.7	1.5	10	2
2035	2.5	0.3	10	2.5	15	4

[a] In 2012, China used 2 million metric tons bio-ethanol and 0.3 million tons bio-diesel [61], which accounted for 2.5% and 0.3% of total gasoline and diesel consumption, respectively.
[b] China plans to expand bio-ethanol and bio-diesel production to 10 million and 2 million tons in 2020, which can increase the fuel blending ratios to 6% in gasoline and 1% in diesel, respectively. We assume the annual production from 2020 to 2035 remains the same as from 2010 to 2020 in the CP scenario.
[c] We assume the biofuel production from 2020 to 2035 increases by 50% comparing CP scenario in FuelBlend and NP scenarios.

Table A.5
Projected electricity generation mix, combustion efficiency and transmission loss of national power grid in China [14].

	Share of coal-based electricity (%)	Combustion efficiency of coal fired power plants (%)	Transmission loss (%)
2010	82	35	6.5
2015	79	36	6.3
2025	70	39	5.5
2035	62	42	5

of vehicle emissions in China always use national average VKT and FC, because of limitations in data availability [56,57]. The national average VKT and FE used in this work are derived from the database built using measurements in about 10 provinces in China. To assess the uncertainty caused by this assumption, we conduct a sensitivity analysis for Beijing and Hubei provinces, one megacity with frequent traffic congestions and less VKT of single car and one less developed province with less traffic congestions and more VKT. We find using provincial VKT and FE will lead to 8% decrease of CO_2 emissions in Beijing and 17% increase in Hubei, respectively, comparing with national average parameters. High-resolution input data are urgently needed to further improve GHG emission estimates for the road transport sector in China, which will require effort from not only the science community but also relevant official departments.

Finally, uncertainties subject to parameter precision, but complete uncertainty evaluations for all parameters are not included in this work. Uncertainty analysis involves much additional work, which requires thorough assessment for all models and parameters. In our previous work, uncertainties of single parameters have been thoroughly researched [2,43,44]. We try to couple a more comprehensive approach, such as Monte Carlo method into the provincial projection framework. At this stage, we conduct an initial uncertainty analysis for predicted vehicle stock to evaluate its influence on policy validity in Section 3.4. We plan to resolve the uncertainties of whole projection model in future work.

5. Conclusion

GHG emissions from on-road vehicles will continue to rise through 2035 under current polices, driven by the significant growth of vehicle activity in major southern provinces. Energy efficiency improvement by current policies is not sufficient to offset the explosive activity increase in this region. According to the sensitivity analysis of alternative policies, we designed an appropriate policy package to curb GHG emissions for China. This integrated policy set includes a reduction in the VKT of urban LDVs by 25%, improving fuel economy by 25% in 2035 comparing 2020, and promotion of electric vehicles and biofuels. The integrated policy, rather than any single policy, is effective to constrain peak GHG emissions by 2030. If this new policy package can be implemented, China will reach its maximum GHG emissions for the road transport sector around 2030.

This work provides a provincial perspective to evaluate to what extent policies should be strengthened to achieve the objective of peak road transportation GHG emissions for the whole China by 2030. A uniform improvement of energy efficiency will have different impacts on GHG emissions by province, because vehicle activity growth varies. Therefore, the regional disparity of vehicle activity growth is considered in this work to make the policy analysis more specific. The method adopted in this work can provide a reference for other sectors to develop policies constraining peak GHG emissions with the consideration of large differences in regional development.

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Appendix A. Parameters adopted in scenarios

See Tables A.1–A.5.

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