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Decarbonization scenarios and carbon reduction potential for China's road transportation by 2060

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The transportation sector is a crucial source of greenhouse gas emissions, and the degree of its low-carbon transformation is closely related to the achievement of China's carbon neutrality. Based on high-frequency passenger vehicle sales data and motor vehicle real-time monitoring big data, we developed a low-carbon transition planning model of China road transport (CRT-LCTP) to explore the pathways toward carbon neutrality. The study found that although the number of new energy vehicles (NEVs) increased four times from 2016 to 2019, the average annual growth rate of road traffic emissions was still as high as 20.5%. The current transportation electrification may only reduce 0.6% of the total emissions in this sector, and it could be increased to 1.4% if the electricity completely came from clean energy. Under the enhanced policy scenario, the transport sector could peak its carbon emissions at around of 2030, with the peak level being 1330.98 Mt. Transportation electrification along could not meet the climate targets in 2060, and the continued inertia of fuel vehicles will slow the path of the road transport toward carbon neutrality, which depends on the forced elimination of fuel vehicles and more substantive decarbonization measures.

INTRODUCTION

China is currently the world's largest energy-consuming and carbon-emitting country, accounting for 30.7% of the world's total carbon emissions in 2020[1]. The transportation sector, especially road transport, is a major contributor to this situation[2–4]. The number of private cars in China increased rapidly from 65 million in 2010 to 244 million in 2020, with an average annual growth rate of 14.14%[5,6]. This has led to a dramatic increase in carbon emissions from China's transport sector from 248 Mt in 2000 to 950 Mt in 2020, accounting for 9% of the country's total carbon emissions[7,8]. With continued economic growth and rapid urbanization, energy demand and carbon emissions from China's transportation industry are expected to grow[9], which may make transportation sector the only sector that cannot reach the peak as scheduled[7,8,10], and poses severe challenges to the low-carbon transition of the transportation sector[11].

Electrification is widely recognized as a powerful way to reduce greenhouse gas emissions (GHG) of transportation[12–14]. Actually, China has ranked first in the world in terms of production, sales, and ownership of NEVs since 2015 (see Supplementary Figs. 1 and 2). and in 2020, the number of NEVs in China reached 4.92 million, accounting for 1.75% of the total number of vehicles (see Supplementary Fig. 3)[15,16]. However, to the best of our knowledge, scarcity of studies systematically assessed the emission reduction potential of China's road transport and the contribution of electrification. The extant research mainly focuses on analyzing the life-cycle GHG emissions of electric vehicles and the associated economic[17–19] and environmental benefits[20,21]. In addition, the quality of energy consumption and fuel efficiency statistics in China's transportation sector is much lower than that in developed countries, which dramatically affects the scientific nature of carbon emissions accounting[22]. As a result, most studies estimated the carbon emissions of road traffic sector using top-down macro frameworks based on annual data from statistical yearbooks, which largely biased the estimation of emissions[23–25].
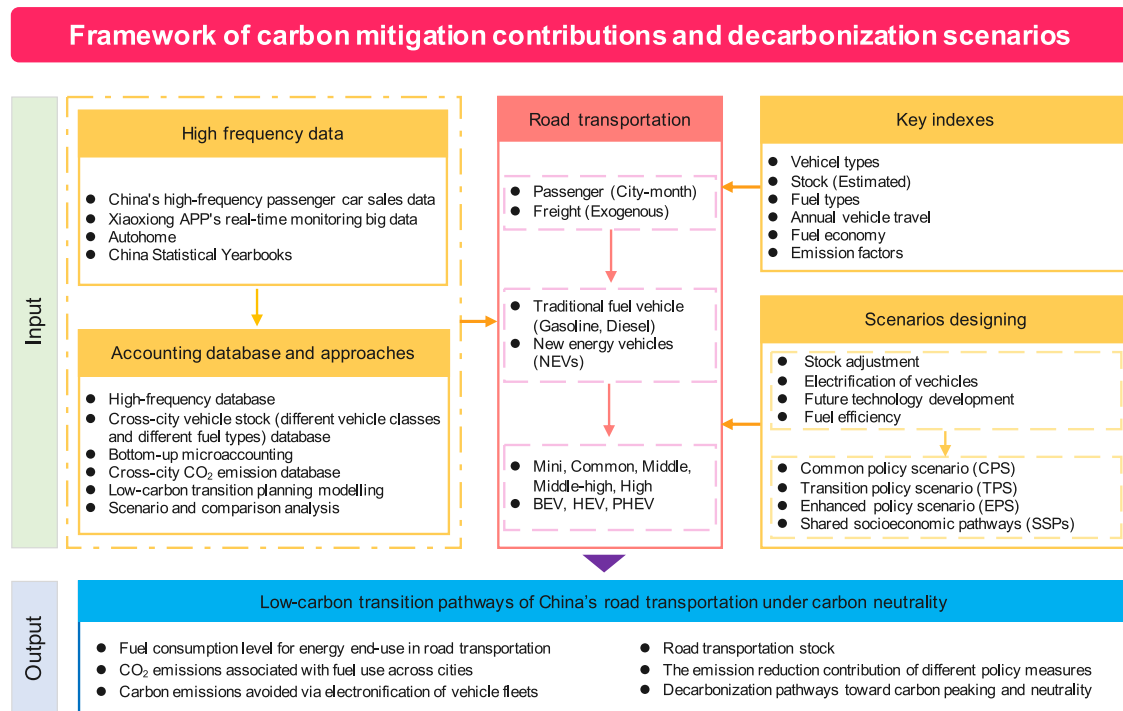
On this basis, we develop a bottom-up microaccounting framework and construct a cross-city vehicle stock (different vehicle classes and fuel types) and CO_2 emission database of China's road transport sector, based on high-frequency passenger car sales data from 2016 to 2019. Further, this paper estimates each vehicle type's actual fuel consumption per 100 km by sampling millions of real-time monitoring data of passenger cars in BearOil app (including different brands, fuel types, and vehicle types), which dramatically reduces the error of CO_2 emission accounting, compared with the existing research using the rough macro data. By developing the CRT-LCTP model, we finally design three decarbonization scenarios of low-carbon transportation transition, estimate the carbon reduction contribution of different policy measures, and assess the difficulty and policy intensity to achieve the "dual carbon" goals (carbon peaking in 2030 and carbon neutrality in 2060). The skeleton of this work is portrayed in Fig. 1.

RESULTS

China's NEVs diffusion and emission estimation: space perspective

As shown in Fig. 2, at the national level, under the support of incentives, the number of NEVs is significantly increasing. In 2016, the stock of NEVs increased from 0.98 million in 2016 to 3.81 million in 2019, with an average annual growth rate of 57.27%. The development of NEVs presents a significant combined effect at the regional level. In 2016, the numbers of NEVs in the eastern, central, and western regions were 643.81 thousand, 19.80 thousand, and 13.88 thousand, respectively, and these values

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Framework of carbon mitigation contributions and decarbonization scenarios

Input

High frequency data
- China's high-frequency passenger car sales data
- Xiaoxiong APP's real-time monitoring big data
- Autohome
- China Statistical Yearbooks

Accounting database and approaches
- High-frequency database
- Cross-city vehicle stock (different vehicle classes and different fuel types) database
- Bottom-up microaccounting
- Cross-city CO_2 emission database
- Low-carbon transition planning modelling
- Scenario and comparison analysis

Road transportation
- Passenger (City-month)
- Freight (Exogenous)
- Traditional fuel vehicle (Gasoline, Diesel)
- New energy vehicles (NEVs)
- Mini, Common, Middle, Middle-high, High
- BEV, HEV, PHEV

Key indexes
- Vehicel types
- Stock (Estimated)
- Fuel types
- Annual vehicle travel
- Fuel economy
- Emission factors

Scenarios designing
- Stock adjustment
- Electrification of vechicles
- Future technology development
- Fuel efficiency
- Common policy scenario (CPS)
- Transition policy scenario (TPS)
- Enhanced policy scenario (EPS)
- Shared socioeconomic pathways (SSPs)

Output

Low-carbon transition pathways of China's road transportation under carbon neutrality
- Fuel consumption level for energy end-use in road transportation
- CO_2 emissions associated with fuel use across cities
- Carbon emissions avoided via electronification of vehicle fleets
- Road transportation stock
- The emission reduction contribution of different policy measures
- Decarbonization pathways toward carbon peaking and neutrality

Fig. 1 Framework of high-frequency CO_2 accounting and decarbonization scenario analysis. (Input: Four databases for high-frequency historical accounting, including cross-city vehicle stock and cross-city CO_2 emissions based on the bottom-up microaccounting method; decarbonization scenarios of low-carbon transportation transition based on key indexes; the carbon reduction contribution of different policy via the proposed CRT-LCTP model. Output: low-carbon transition pathways of China's road transportation toward carbon neutrality).

increased to 2.57 billion, 819.1 thousand, and 423.7 thousand in 2019, with annual growth rates of 58.66, 60.52, and 45.07%, respectively. There were only four cities surpassing the threshold of 50,000 NEVs in 2016, and the number increased to 15 in 2019, and these cities are all located in the eastern and central regions, except for Chengdu, Chongqing, and Liuzhou (Supplementary Notes 1 and 2). The higher growth of NEV stocks in the eastern and central regions is mainly due to their higher economic development, excellent supporting facilities, and stronger consumer market demand.

The CO_2 emissions of road passenger transport show a significant increasing trend, as shown in Fig. 2, with corresponding emissions increasing from 414.59 Mt in 2016 to 725.77 Mt in 2019 and presenting an average annual growth rate of 20.5%. At the regional level, the eastern coastal regions contribute half of the country's total road traffic emissions, followed by the central and western regions. Actually, the majority of the top 10 city emitters are located in the eastern and central regions, except the typical new first-tier cities, i.e., Chengdu and Chongqing (Supplementary Note 2). The high levels of economic development and per capita vehicle stock (mainly traditional fuel vehicles) could tell most of the story. By contrast, the rapid development of transportation infrastructure construction, e.g., high-speed roads, partially explains the high growth rate of road traffic emissions in the central and western regions. Along with the expectation of economic prosperity, carbon emissions in these regions could greatly increase in the future without substantial electrification.

China's NEVs development paths and CO_2 estimation: time perspective

We could observe different time features between the sales of traditional fuel vehicles and NEVs, as portrayed in Fig. 3. During the period, the average annual growth rate of gasoline vehicles and diesel vehicles dropped by −6.25 and −4.80%, respectively. In contrast, NEV sales, particularly battery electric vehicles (BEVs),

increased year by year, with an average annual growth rate of 45.76%. The annual sales peak of NEVs is in the second half of the year, especially in December at which time most promotion activities happened (Fig. 3a). In addition, every July is the liquidation time of the previous year's new energy subsidies and the earliest month of the preallocation funds for the sales of NEVs in that year, which also explains the surge in NEV sales in the second half of the year. This indicates the significant role of policy incentives in the prosperity of NEV market[26].

We also estimated CO_2 emissions from vehicles with different fuel types and their differences over time, as shown in Fig. 3c, d. Obviously, gasoline vehicles have the largest carbon emissions, followed by diesel vehicles, BEVs, PHEVs, and HEVs, which are jointly determined by vehicles' stock, sales, and fuel economy with different fuel types. In terms of time scale, summer and winter are the peak emission periods of the year, especially winter, at which time residents are more likely to choose private cars, taxis or online car-hailing to meet their travel needs than public transportation. Actually, the number of online car-hailing users in China reached 400 million in 2019[27], and the large-scale development of online car hailing may have an induced effect of emissions. Although the improvement in the road traffic sharing level reduces car purchase intention to a some extent[28], the total mileage of trips does not significantly decrease, which leads to an increase in carbon emissions[29–31]. It is therefore also vital to promote the electrification of online car-hailing services[32].

The emission reduction potential of road transport electrification mainly comes from the difference in emission intensity between electric vehicles and traditional fuel vehicles[33]. Basically, we assume that the electricity consumed comes from thermal power by default, according to the current situation. As shown in Fig. 3e, f, the emission reduction caused by vehicle electrification shows a significant increase trend. From 0.94 Mt in 2016 to 4.00 Mt in 2019, the average annual growth rate reached 61.81%. If all the electricity consumed by electric cars comes from clean sources,
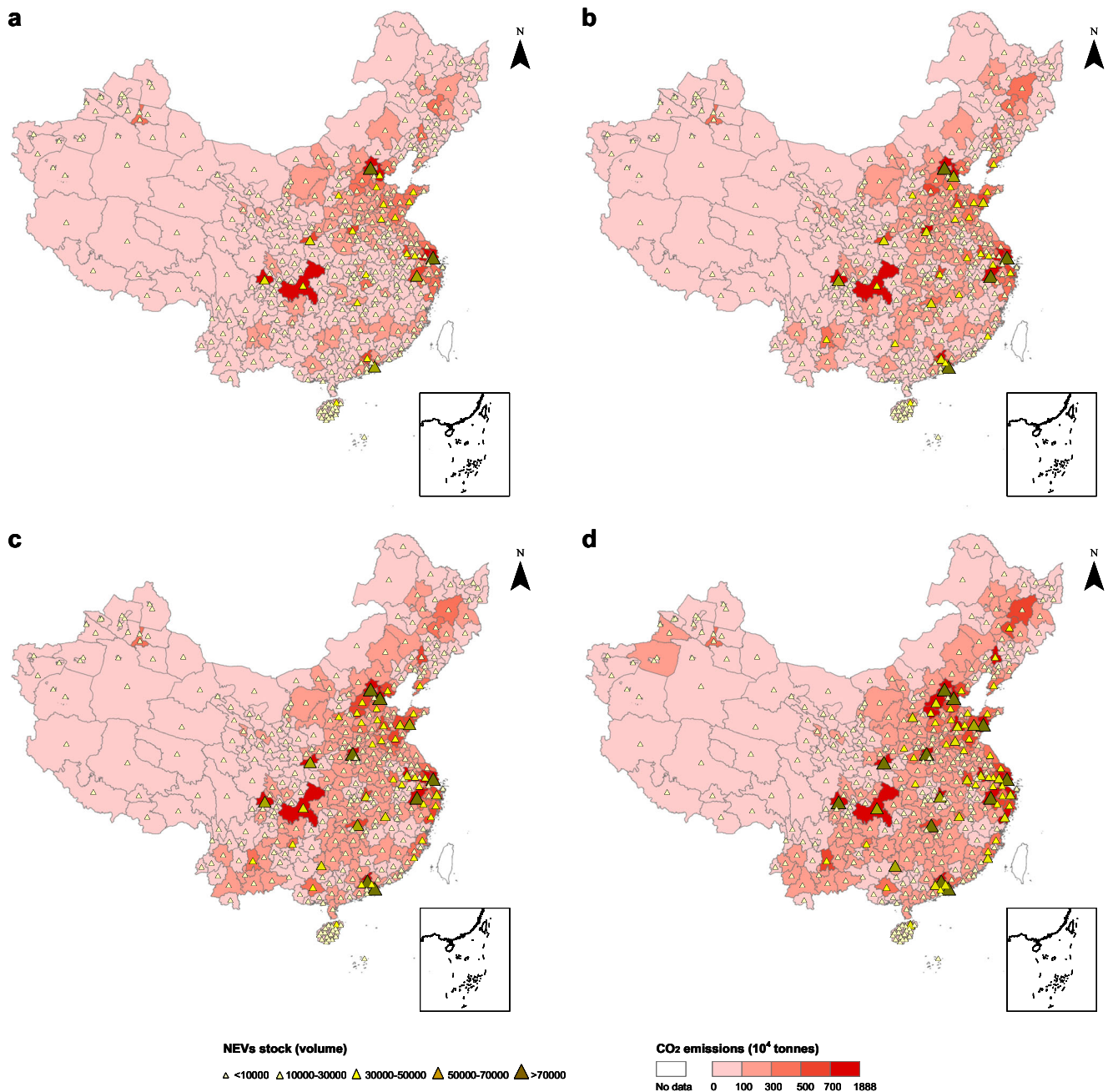
Fig. 2 Distribution of NEV stock and estimation of CO$_2$ emissions for China passenger road transport 2016–2019. a–d (The size and color of the triangle represent the volume of NEV stocks; the background color on the map represents the estimated CO$_2$ emissions.) Source data are provided in the Source Data file.

such as hydropower, then the reductions will expand to 1.81 Mt in 2016 and 10.14 Mt in 2019. Figure 3d also shows the emission reduction potential of different classes, and we find that MCC and MHCC gasoline cars (engine displacement in the range of 1.6–4 L) have the largest potential of carbon reduction, given its dominant role in passenger car consumption. This emphasizes the significance of regulating high-emission vehicle sales to control road traffic emissions (see Supplementary Note 3 for more details).

Relationships among vehicle stock, CO$_2$ emissions, and economic development

The level of economic development of a region largely determines the purchasing power of consumers, which in turn determines the car stock and sales and related carbon emissions. Generally, the higher the per capita GDP is, the higher the vehicle stock and the associated carbon emissions[25,34]. Compared with 2016, in 2019, the average per capita GDP growth of the 11 provincial capital cities in eastern China was 16.15% (Fig. 4). However, the stock of passenger cars and their CO$_2$ emissions reached 37.6% and 70.2%, respectively. This is particularly true for Guangzhou and Beijing, despite the rapid expansion of motor vehicles in Beijing has been restricted by policies such as lottery and driving restrictions (Supplementary Note 4). Overall, the average per capita GDP growth rate of provincial capitals in the central region is 2.22% higher than that of provincial capitals in the eastern region. This is also true for the growth rates of vehicle ownership and CO$_2$ emissions. To be
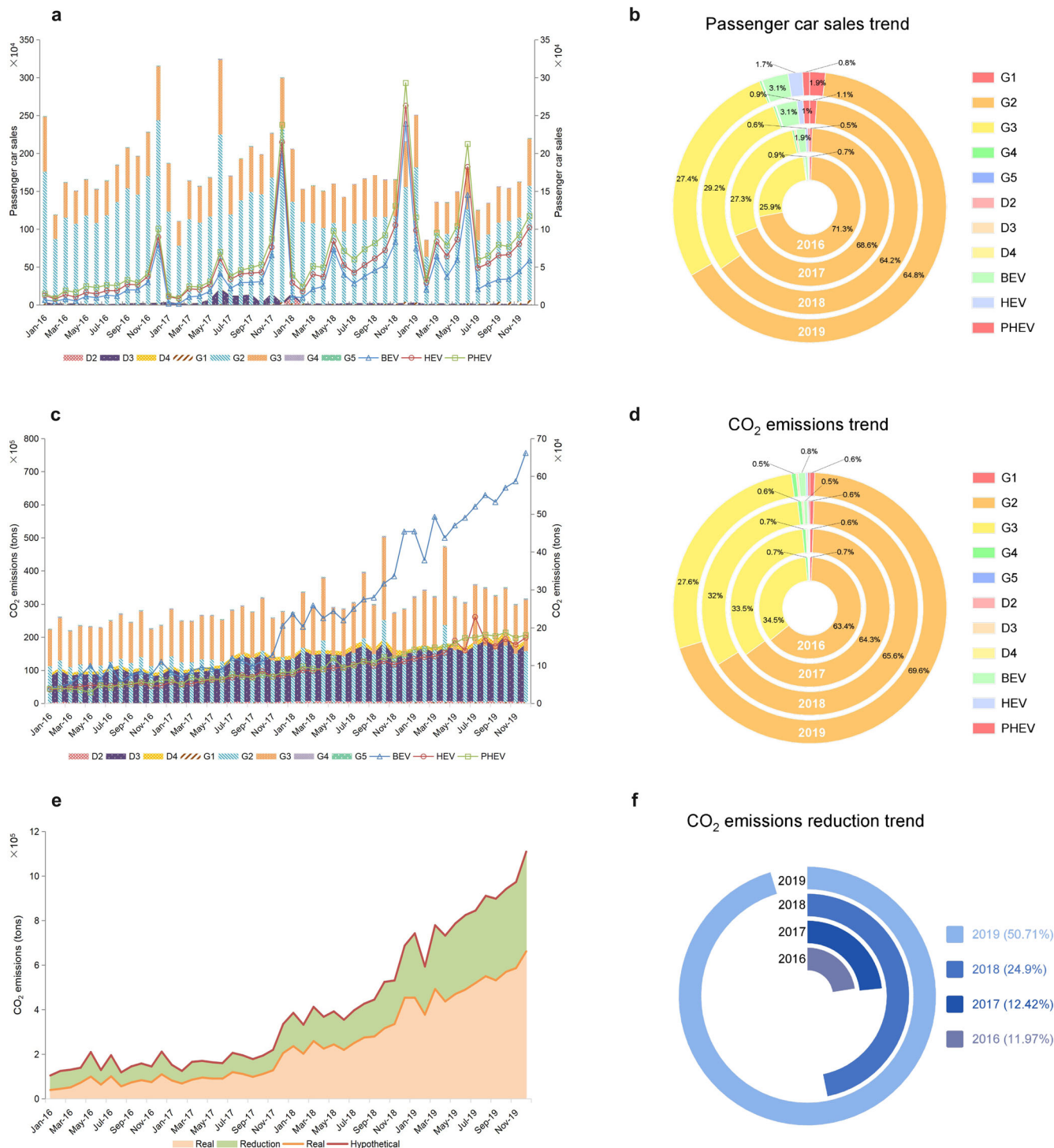
Fig. 3 Month-to-month sales, CO₂ emissions, and carbon reduction due to vehicle electrification for China's road passenger transport.
a Passenger car sales; **b** passenger car sales trend; **c** road passenger transport CO_2 emissions; **d** road passenger transport CO_2 emissions trend; **e** carbon reduction due to vehicle electrification; **f** trend of carbon reduction due to vehicle electrification (G1 = Gasline Mini Car; G2 = Gasoline Common Class Car; G3 = Gasoline Middle Cass Car; G4 = Gasoline Middle-High Class Car; G5 = Gasoline High Class Car; D2 = Diesel Common Class Car; D3 = Diesel Middle Cass Car; D4 = Diesel Middle-High Class Car; Hybrid Electric Vehicle = HEV; Plug-in Hybrid Electric Vehicle = PHEV; Real = electricity from thermal power; Reduction = real carbon reduction due to vehicle electrification; Hypothetical = electricity from clean energy). Source data are provided in Source Data file.

specific, Wuhan has the most significant increase in CO_2 emissions, as high as 2207%, while Zhengzhou is the largest emitter owing to the so-called "stock" effect of motors (Zhengzhou ranks first in terms of vehicle ownership in the central provinces, Fig. 2).

In contrast, the western region had the most significant increase in per capita GDP during the studied period, with an average increase of 19.7% in all provincial capitals. The rise in passenger car stock and its carbon emissions is larger than that in the eastern region but smaller than that in the central
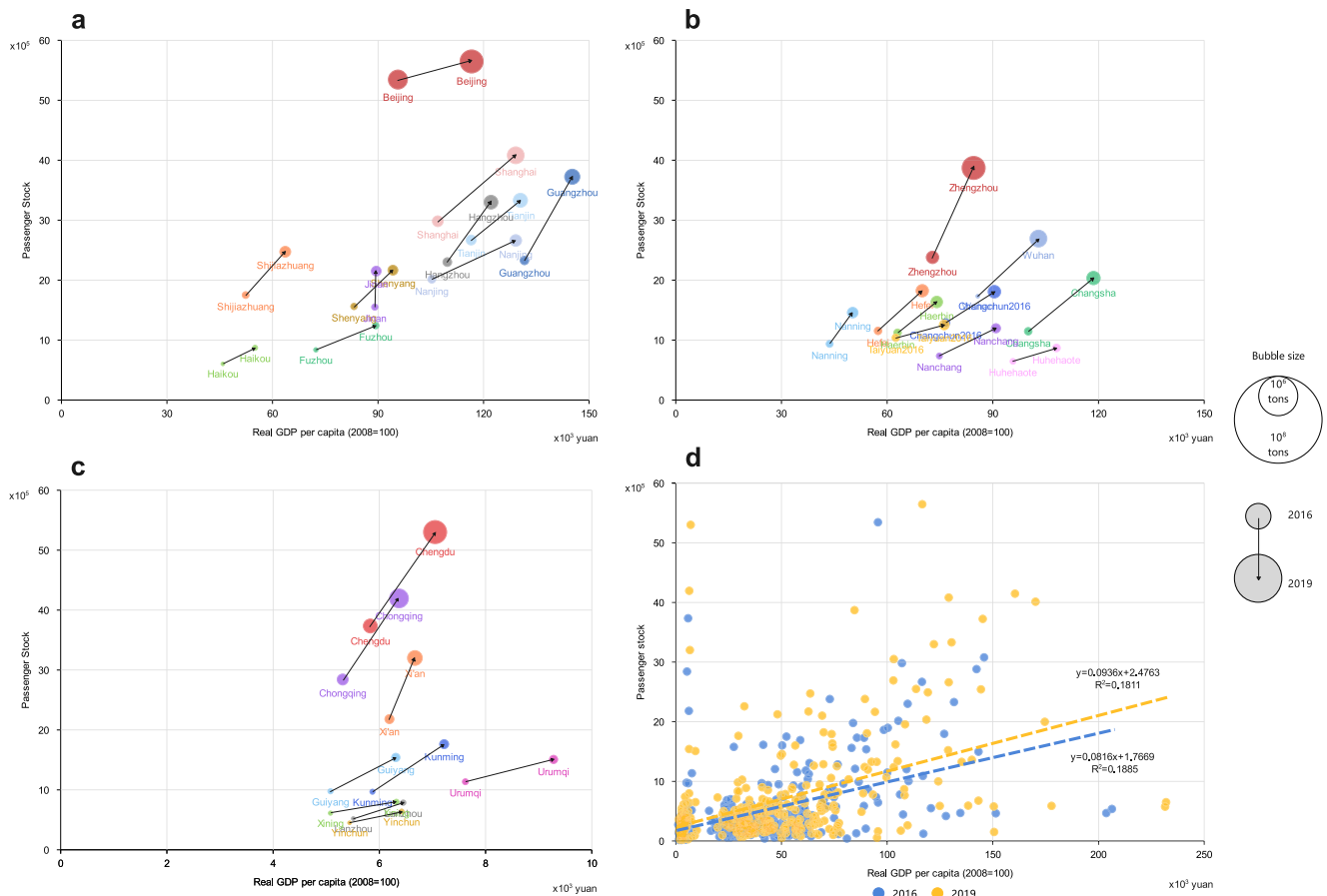
Fig. 4 Relation dynamics of road passenger stock, GDP per capita (2008 = 100), and CO$_2$ emissions from 2016 to 2019. a 11 provincial capitals of Eastern China; **b** 10 provincial capitals of Central China; **c** 9 provincial capitals of Western China; **d** relationship between passenger car stock and economic development in 291 prefecture-level cities. The two bubbles (the small and big bubble) in subfigures show carbon emissions in 2016 and 2019 respectively, and the size gives the number of estimated emissions.

region. The relations among vehicle stock, CO$_2$, and economic growth are true in most western cities, except Xi'an and Lanzhou. Actually, economic growth of the two provincial capitals was slow, but their vehicle ownership and carbon emissions have grown enormously, and this situation also occurs in typical eastern cities, like Shenyang, Hangzhou, Tianjin, and Jinan. This provides evidence that economic development is not always positively and linearly related to residents' willingness and ability to purchase a car.

From a national perspective, we observe a highly positive correlation between passenger car ownership and per capita GDP (Fig. 4d), and the relationship between the two gradually strengthened over the period. In 2016, an extra 1% increase in per capita GDP is associated with a 8.2% increase in passenger vehicles, and this value increased to 9.4% in 2019. Given a lower car ownership per thousand people in China (compared with the developed economies) and a sustained economic growth expectation, residents' willingness to buy motor vehicles will dramatically increase in the future. In addition, the restriction policy does alleviate road congestion caused by fuel vehicles to a certain extent, but in the long run, whether it effectively reduces CO$_2$ emissions and air pollutants is still controversial[35–38]. Therefore, how to coordinate economic growth with structural adjustment in the automobile industry (vehicle electrification) is of great significance to long-term low-carbon transformation of the traffic sector.

Low-carbon transition pathways of road transportation

By developing a CRT-LCTP model, we study the low-carbon transition pathways of China's road transport across various scenarios (see "Methods" and Scenario setting), and the results are portrayed in Fig. 5a. As the number of traditional fuel vehicles increases, China's road transport CO$_2$ emissions will increase significantly. Under the BAU scenario, China's road transport CO$_2$ emissions will increase from 1340.80 Mt in 2020 to 1683.66 Mt in 2030, with an annual growth rate of approximately 2.3%. The emissions will peak in 2058, corresponding to the peak level of 2563.08 Mt. However, the peak time could be advanced to 2045 and 2034, respectively under the CPS and TPS, despite they are still later than the committed 2030. Thus, peak the emissions of transport sector in time depends on more intensified policies. Indeed, when moving to the most stringent scenario, i.e., the EPS, road traffic emissions can peak in 2031, roughly consistent with the promised time of the NDC target, and the corresponding peak level is reduced by 48.3% relative to the BAU scenario.

From Fig. 5b–d, we find that the maximum contribution of emission reduction under the three policy scenarios all comes from the stock adjustment, and the contribution levels are 75.15, 63.74, and 59.57%, respectively. The contribution of electrification increases significantly with the strengthening of policy intensity, from 17.61% under the CPS to approximately 33.10% under the EPS. The contribution of technological progress, such as fuel efficiency improvement, to emission reduction is relatively limited, with an average level of approximately 2%, and it is much lower than that of 'Other' factors, i.e., 5–16% on average.
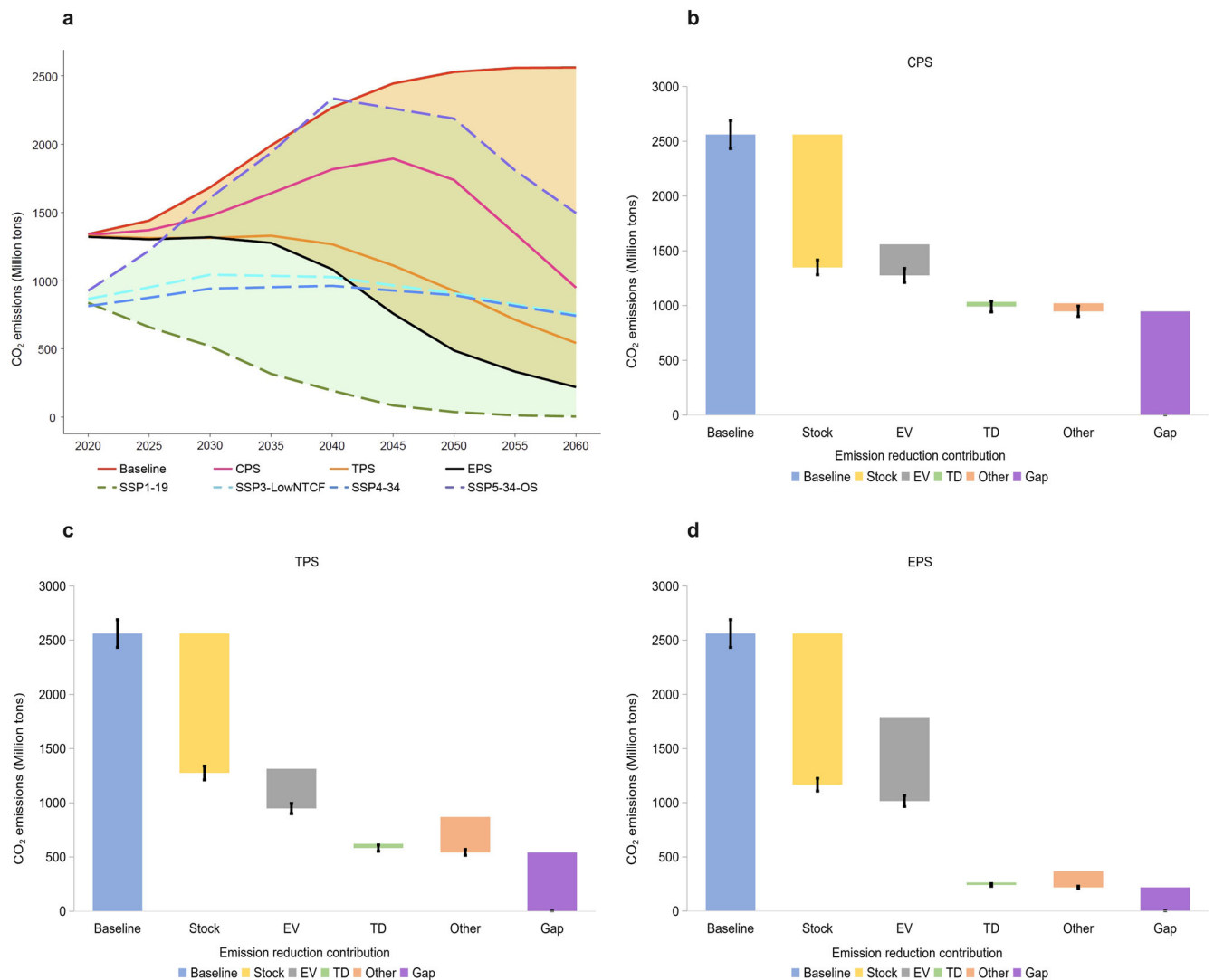
Fig. 5 CO$_2$ emissions pathways (2020–2060) and distribution of carbon mitigation contribution (2060) for China's road transportation. **a** CO$_2$ emissions of road transportation across different scenarios (2020–2060); **b** mitigation contribution under the CPS; **c** under the TPS; **d** and under the EPS (Stock adjustment = Stock, electrification of vehicles = EV, =TD, Other factors (public transport rate, emission standard control, operation efficiency, etc.) =Other, Zero emissions gap = Gap). 'Other' includes factors that are not considered in the EV and TD scenarios, such as the increase in the public transportation share, share trips, emission standard control, etc.

Overall, due to the persistence of traditional fuel vehicles (Supplementary Fig. 4), it is difficult to achieve net-zero emissions in the road traffic sector by 2060, and it is true when moving to the results under the SSPs (see Supplementary Note 5 for details). However, the optimistic auto electric transformation will finally restructure the future of road transport structure and then determine the long-term trend of carbon emissions, especially in the passenger transport department. In addition, challenges in the low-carbon transition of freight transport[39,40] also explains the difficulty in achieving carbon neutrality in road transport (see Supplementary Note 6). Therefore, the realization of carbon neutrality in the transport sector may further rely on the forced phase-out of fuel vehicles, disruptive innovation in the transport system, and the structural adjustment of freight transport from road to rail and water.

DISCUSSION

The low-carbon transformation of China's road transport sector is key to achieving the country's dual carbon goals. Based on China's high-frequency passenger vehicle sales data and real-time vehicle monitoring big data, we find that the ownership of NEVs and CO$_2$ emissions from road traffic showed a significant growth trend, with average annual growth rates of 57.3 and 20.5%, respectively. Among them, the eastern coastal region had the largest emissions, with road traffic emissions accounting for half of the region's total emissions, but the central region had the largest annual growth rate of 22.2%. A direct and significant positive correlation between economic development and car ownership is also found, which implies that the high level of economic development generally determines the high ownership of vehicles and high emission level.

Under the influence of the economic development level, population density, transportation infrastructure construction, and other factors, road transport passenger CO$_2$ emissions and NEV ownership show significant regional heterogeneity. We also observed a significant increase in emissions reduction from the electrification of vehicles. Even if all electricity consumed by electric vehicles came from coal, emissions reductions from electrification increased nearly fourfold between 2016 and 2019, and the increase could be tenfold, if the consumed power were

from clean source. Therefore, cleanliness of the power supply is the key to reduce emissions of transportation electrification.

The low-carbon transition path analysis shows that although the road traffic emissions will peak in 2058 under the BAU, this time point in the EPS can be advanced to almost the same time as it is committed in the NDC target. Transportation electrification and total motor vehicle control are the policies that contribute the most to emission reductions. The former can reduce emissions by up to 33%, while the effect of the latter can exceed 55%. Most importantly, we found it is challenging to achieve net-zero emissions in the road transportation sector by 2060 due to the inertia regarding fuel vehicles in the transportation system. Therefore, in the future, road transport carbon neutrality may depend on fuel vehicles' forced phase-out and a structural transformation of the NEV-led road transportation system, which in turn relies a series of sound economic incentive policies and an improved legal and standard system. Moreover, the low-carbon innovation of freight transport and the structural adjustment of road freight transport to water transport and railways are also crucial to achieving China's carbon neutrality vision.

METHODS
This paper constructed the CRT-LCTP model for China's road low-carbon transportation transition based on the LEAP model. The specific model structure and technical details are given as follows. First, energy consumption is calculated as below:

$$EC = \sum_{i=1}^{n} AL_i \times VS_i \times EI_i \qquad (1)$$

where AL_i, VS_i and EI_i represent the activity level, vehicle stock, and energy intensity of vehicle type i, respectively.

$$VS_i = \sum_{t=1}^{n} \sum_{v=1}^{m} Sal_{i,v} \times Sur_{i,t-v} (i = 1, 2, \cdots, n) \qquad (2)$$

where $Sal_{i,v}$ represents sales of vehicle type i in vintage year v and $Sur_{i,t-v}$ is the survival rate of vehicle type i after $t-v$ years of use. Second, we give energy intensity of vehicles, i.e.,

$$EI_i = \sum_{j=1}^{m} AVT_i \times FE_{i,j} \times FS_{i,j} (i = 1, 2, \cdots, n) \qquad (3)$$

where AVT_i is the monthly vehicle travel mileage of vehicle type i, $FE_{i,j}$ is the fuel economy of fuel type j used by vehicle type i, and $FS_{i,j}$ represents the fuel share of fuel j in vehicle type i. The CO_2 emissions are estimated via the product of energy consumption and emission factor, i.e.,

$$CE = EC_j \times EF_j \qquad (4)$$

where CE is the amount of CO_2 emissions and EC_j and EF_j represent the energy consumption and emission factors of fuel type j, respectively. The estimation of emission reduction potential can be seen in Supplementary Note 7.

Scenario settings
The baseline (BAU) scenario can be regarded as a scenario without policy or reference and is mainly used for comparison with other scenarios with policy implementation. In the BAU scenario, it is assumed that China's road transport sector will continue to develop according to the current situation in 2019, without considering any new policies and measures implemented by the government after 2019. According to China's car scrapping standards, private cars, taxis, and buses must be scrapped after 15 years, 8 years, and 5 years, respectively. Because taxis and buses account for a relatively small proportion, this paper sets the scrap rate of all models divided by displacement as 15 years. Moreover, the mini truck (MT) has a life expectancy of 12 years,

and the other three (Light Truck, LT; Medium Truck, MT; Heavy Truck, HT) have a life expectancy of 15 years. According to the State Information Center, China's car ownership will peak at 600 million units[41]. Therefore, assuming stable macroeconomic growth persists at a conservative rate, passenger car sales and truck sales will grow by 5% from 2020 to 2030, 3% from 2030 to 2040, 1% from 2040 to 2050, and 0.5% from 2050 to 2060. As a sales benchmark, the proportion of model sales stock remains unchanged. In 2030 and 2060, NEV sales in new passenger cars will account for 25 and 55%, respectively, and NEV sales in trucks will account for 4 and 10%, respectively.

In addition to the BAU scenario, three policy scenarios were designed, namely, the common policy scenario (CPS), transition policy scenario (TPS), and enhanced policy scenario (EPS). Specifically, the CPS is based on the BAU scenario. There are no significant changes in economic patterns, passenger and freight structure, or transportation technology, which are gradually evolving. The TPS further strengthens and expands the general policy scenario, optimizes the traffic structure, develops traffic technology and forms the transformational policy scenario. The EPS is more stringent than the TPS, aiming for the carbon peak around 2030 and carbon neutrality by 2060. This paper considers the following three key policy indicators for emission reduction policies and measures: stock adjustment, promotion of NEVs, and technological progress (reduction in fuel consumption per 100 km) in the three scenarios. For more description and reference sources of the key indicators, see Supplementary Table 1.

Stock adjustment. As of June 2020, the number of cars per 1000 people in China was 193. The improvement in income level and the road transport environment is expected to reach 238 vehicles per 1000 people in 2025 and 289 cars per 1000 people in 2030[41]. Considering population density, cultural habits, and other factors, it is more reasonable to consider Japan and South Korea as the reference objects for analyzing automobile ownership per thousand people in China. The saturation point is 400–450 cars per thousand people. Therefore, we take 400 per thousand (0.4 vehicles per person) multiplied by 1.45 billion (saturation point), that is, approximately 600 million. By stimulating consumption and other means, the demand space will be released, and car ownership will reach its peak as soon as possible. Therefore, the vehicle stock will reach 370 million in 2030 and 495 million in 2060 under the CPS.

Electrification of vehicles. According to the State Information Center forecast, NEV sales will account for approximately 20% of the total new car sales by 2025[41]. In addition, NEV sales will continue to grow in 2020, with NEV sales in passenger vehicles exceeding 1.3 million. From this perspective, the number of NEVs will exceed 5.1 million in 2020. In 2030 and 2060, the penetration rate of NEVs in vehicle ownership needs to reach 20 and 100%, respectively. Therefore, NEV sales in 2030 and 2060 will account for 40 and 80% of all new passenger car sales under the CPS, and NEVs will account for 5 and 17% of all new truck sales, respectively.

Technological development. With the development and upgrading of transportation technology, fuel consumption (power consumption) per 100 km decreases. According to the NEV Industry Development Plan (2021–2035), the average power consumption of BEVs will be reduced to 12 kWh/100 km by 2025. Therefore, it is assumed that the fuel economy of traditional fuel vehicles decreases by 0.5 based on the basic data in 2019, and the average power consumption of NEVs is 12 kWh/100 km under the CPS. See Supplementary Tables 2 and 3 for detailed settings.

Data
Stock and sales. First, according to the high-frequency passenger vehicle sales database and the National Bureau of Statistics, we

select 2015 as the base year and divide the fuel types into diesel, gasoline, and NEVs. The diesel and gasoline vehicles are further divided into five classes according to the displacement (Mini: <1 L; Common Class: 1.0–1.6 L; Middle Class: 1.6–2.5 L; Medium-high Class: 2.5–4 L; High Class: >4 L). NEVs are divided into BEVs, plug-in hybrid vehicles (PHEVs) and hybrid vehicles (HEVs). Considering that the data for dual-fuel vehicles are very limited, these vehicles are eliminated. Second, the proportions of diesel, gasoline and NEVs (different types and fuels) from 2016 to 2019 are calculated based on the entire sample mean of each label in the database. Among them, the NEV data are calibrated according to the annual data published by the Ministry of Public Security and relevant institutions. Third, since the National Bureau of Statistics does not distinguish passenger and freight vehicle ownership at the level of prefecture-level cities, we selected the share of vehicle ownership among local citizens in the number of civil vehicles in the province as the proportion of passenger vehicles owned in prefecture-level cities.

Scrap rate. Scrap rate = scrap/stock. Considering the unity of the data source, we first calculated the annual sales volume. We then converted the annual sales volume and scrap volume into monthly sales volume and scrap volume to calculate the monthly scrap rate.

Fuel consumption per 100 km and monthly mileage. We calculated the actual fuel consumption per 100 km of different types by matching the BearOil app ((www.xiaoxiongyouhao.com (accessed on 18 May 2021))) and Autohome website based on millions of data observations. Similarly, the monthly average mileage is the actual mileage of monthly frequency calculated by using the above method.

CO_2 emission factor. In this paper, the gasoline and diesel emission factors are IPCC values[42]. In addition, the power emission factor selects different carbon dioxide emission factors based on six regional power grids in China. The detailed parameter settings for road traffic are shown in Supplementary Tables 2–4.

Reporting summary
Further information on experimental design is available in the Nature Portfolio Reporting Summary linked to this Article.

DATA AVAILABILITY
The high-frequency passenger vehicle sales database is restrictive, and the generated emission dataset could be accessed upon requests.

CODE AVAILABILITY
The source codes for the dataset and model developed in this paper can be accessed on request.

REFERENCES
1. British Pertrolem (BP). *Statistical Review of World Energy – 2021 China energy market in 2020* BP. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs (2021).
2. International Energy Agency (IEA). *World Energy Statistics (2016–2021)* IEA. https://www.iea.org/statistics/relateddatabases/worldenergystatisticsandbalances/ (2021).
3. Mi, Z. et al. Chinese CO_2 emission flows have reversed since the global financial crisis. *Nat. Commun.* **8**, 1712 (2017).
4. Du, H., Chen, Z., Peng, B., Southworth, F. & Wang, Y. What drives CO_2 emissions from the transport sector? A linkage analysis. *Energy* **175**, 195–204 (2019).
5. China Association of Automobile Manufactures CAAM. http://www.caam.org.cn/ (2021).
6. National Bureau of Statistics of China (NBSC). *China Energy Statistical Yearbook 1991–2021* National Bureau of Statistics of China & National Energy Administration of China. http://www.stats.gov.cn/ (2021).
7. IEA. An *energy sector road map to carbon neutrality in China* IEA. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china (2021).
8. IEA. *Global Energy Review 2021* IEA. https://www.iea.org/reports/global-energy-review-2021 (2021).
9. Wang, Z. & He, W. CO_2 emissions efficiency and marginal abatement costs of the regional transportation sectors in China. *Transp. Res. Part D: Transp. Environ.* **50**, 83–97 (2017).
10. McCollum, D. L. et al. Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. *Nat. Energy* **3**, 664–673 (2018).
11. Duan, H. et al. Assessing China's efforts to pursue the 1.5 degrees C warming limit. *Science* **372**, 378–385 (2021).
12. Milovanoff, A., Posen, I. D. & MacLean, H. L. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. *Nat. Clim. Change* **10**, 1–6 (2020).
13. Yang, F., Xie, Y., Deng, Y. & Yuan, C. Predictive modeling of battery degradation and greenhouse gas emissions from US state-level electric vehicle operation. *Nat. Commun.* **9**, 1–10 (2018).
14. Li, J. & Yang, B. Analysis of greenhouse gas emissions from electric vehicle considering electric energy structure, climate and power economy of ev: a China case. *Atmospheric Pollut. Res.* **11**, 1–11 (2020).
15. Sovacool, B. K., Abrahamse, W., Zhang, L. & Ren, J. Pleasure or profit? Surveying the purchasing intentions of potential electric vehicle adopters in China. *Transp. Res. Part A: Policy Pract* **124**, 69–81 (2019).
16. The Ministry of Public Security of the People's Republic of China (MPSRPC). *National Motor Vehicle and Driver in 2020* MPSRPC. https://app.mps.gov.cn/gdnps/zc/index.jsp (2020).
17. Liang, X. et al. Air quality and health benefits from fleet electrification in China. *Nat. Sustain.* **2**, 962–971 (2019).
18. Qiao, Q., Zhao, F., Liu, Z., Hao, H. & Amer, A. A. Life cycle cost and GHG emission benefits of electric vehicles in China. *Transp. Res. Part D: Transp. Environ.* **86**, 102418 (2020).
19. Xu, L., Yilmaz, H. Ü., Wang, Z., Poganietz, W. R. & Jochem, P. Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies. *Transp. Res. Part D: Transp. Environ.* **87**, 102534 (2020).
20. Xing, J., Leard, B. & Li, S. What does an electric vehicle replace? *J. Environ. Manage.* **107**, 102432 (2021).
21. Wang, L., Yu, Y., Huang, K., Zhang, Z. & Li, X. The inharmonious mechanism of CO_2, NO_x, SO_2, and PM2. 5 electric vehicle emission reductions in Northern China. *J. Environ. Manage.* **274**, 111236 (2020).
22. Deng, F. et al. A big data approach to improving the vehicle emission inventory in China. *Nat. Commun.* **11**, 1–12 (2020).
23. Pan, D. et al. Methane emission form natural gas vehicles in China. *Nat. Commun.* **11**, 1–10 (2020).
24. Zhang, D. et al. Switching on auxiliary devices in vehicular fuel efficiency tests can help cut CO_2 emissions by millions of tons. *Cell: One Earth* **4**, 135–145 (2021).
25. Peng, L. et al. Alternative-energy-vehicles deployment delivers climate, air quality, and health co-benefits when coupled with decarbonizing power generation in China. *Cell: One Earth* **4**, 1127–1140 (2021).
26. Wang, N., Pan, H. & Zheng, W. Assessment of the incentives on electric vehicle promotion in China. *Transport. Res. Part A: Policy Pract* **101**, 177–189 (2017).
27. China Internet Network Information Center CNNIC. http://www.cnnic.net.cn/ (2021).
28. Vazifeh, M. M., Santi, P., Resta, G., Strogatz, S. H. & Ratti, C. Addressing the minimum fleet problem in on-demand urban mobility. *Nature* **557**, 534–538 (2018).
29. Chai, J., Lu, Q., Wang, S. & Lai, K. Analysis of road transportation energy consumption demand in China. *Transp. Res. Part D: Transp. Environ.* **48**, 112–124 (2016).
30. Frenken, K. Sustainability perspectives on the sharing economy. *Environ. Innov. Soc. Transit.* **23**, 1–2 (2017).
31. Namazu, M., MacKenzie, D., Zerriffi, H. & Dowlatabadi, H. Is carsharing for everyone? Understanding the diffusion of carsharing services. *Transp. Policy* **63**, 189–199 (2018).
32. Luna, T. F., Uriona-Maldonado, M., Silva, M. E. & Vaz, C. R. The influence of e-carsharing schemes on electric vehicle adoption and carbon emissions: an emerging economy study. *Transp. Res. Part D: Transp. Environ.* **79**, 102226 (2020).
33. Winkler, S. L. et al. Vehicle criteria pollutant (pm, no x, co, hcs) emissions: how low should we go? *npj Clim. Atmos. Sci.* **1**, 1–5 (2018).
34. Vilchez, J. J. G., Jochem, P. & Fichtner, W. Interlinking major markets to explore electric car uptake. *Energy Policy* **144**, 111588 (2020).

35. Koch, N., Naumann, L., Pretis, F., Ritter, N. & Schwarz, M. Attributing agnostically detected large reductions in road CO_2 emissions to policy mixes. *Nat. Energy* **7**, 1–10 (2022).
36. Sun, C., Zheng, S. & Wang, R. Restricting driving for better traffic and clearer skies: did it work in Beijing? *Transp. Policy* **32**, 34–41 (2014).
37. Viard, V. B. & Fu, S. The effect of Beijing's driving restrictions on pollution and economic activity. *J. Public Econ.* **125**, 98–115 (2015).
38. Sun, C., Xu, S., Yang, M. & Gong, X. Urban traffic regulation and air pollution: a case study of urban motor vehicle restriction policy. *Energy Policy* **163**, 112819 (2022).
39. Greene, S. & Cristiano, F. Carbon offsets for freight transport decarbonization. *Nat. Sustain.* **2**, 994–996 (2019).
40. Luo, X. et al. Regional disparity analysis of Chinese freight transport CO_2 emissions from 1990 to 2007: driving forces and policy challenges. *J. Transp. Geogr.* **56**, 1–14 (2016).
41. The State Information Center SIC. http://www.sic.gov.cn/index.htm (2021).
42. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories* IPCC. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf (2006).

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AUTHOR CONTRIBUTIONS

Q.L. and H.D. conceived and designed this study. Q.L., H.S., and Y.L. analyzed the data; B.P. and T.W. collected the data; Q.L. developed and ran the simulations. Q.L. and H.D. wrote the manuscript. H.D. and S.W. provided general advice and supervised the research. All the authors revised the paper.

COMPETING INTERESTS

The authors declare no competing interests.

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