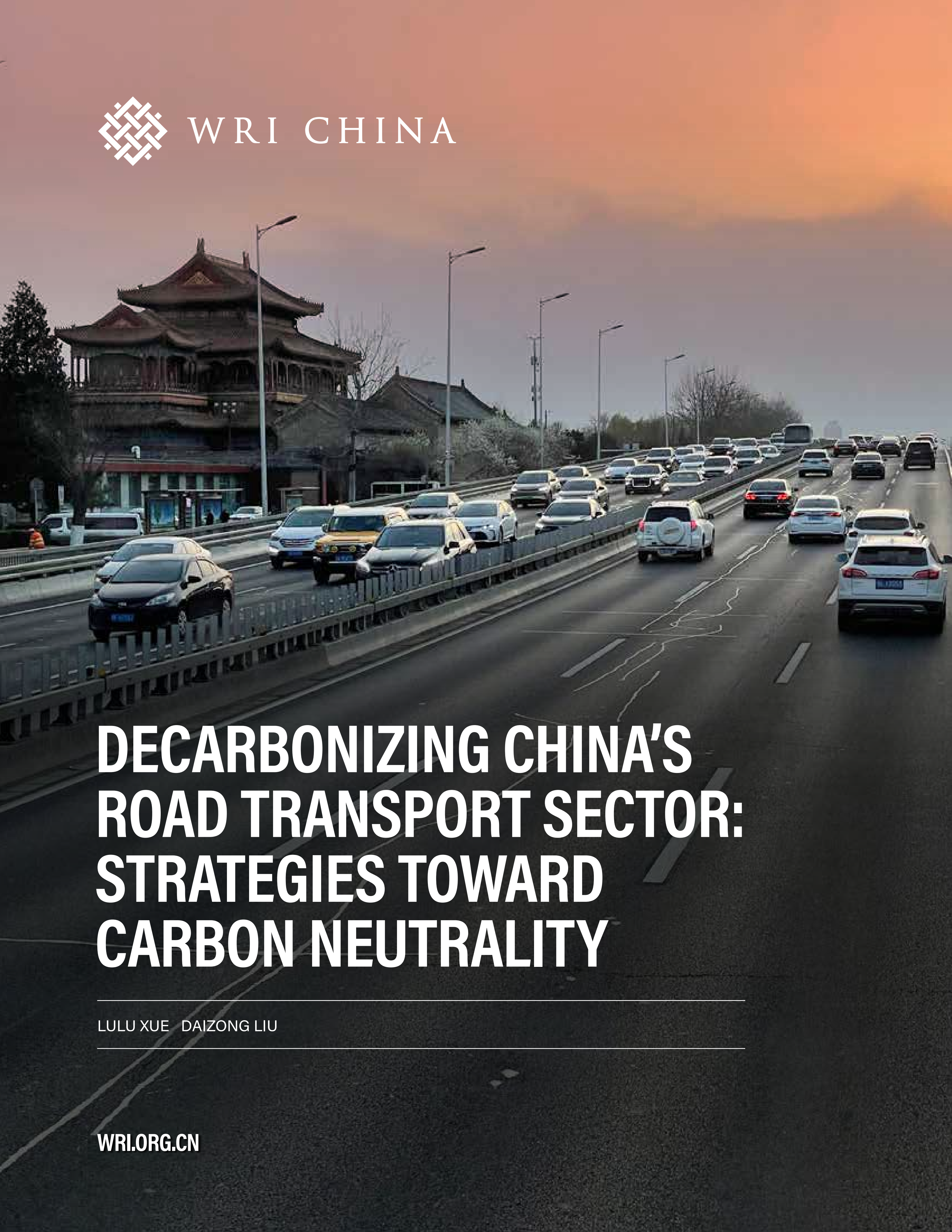
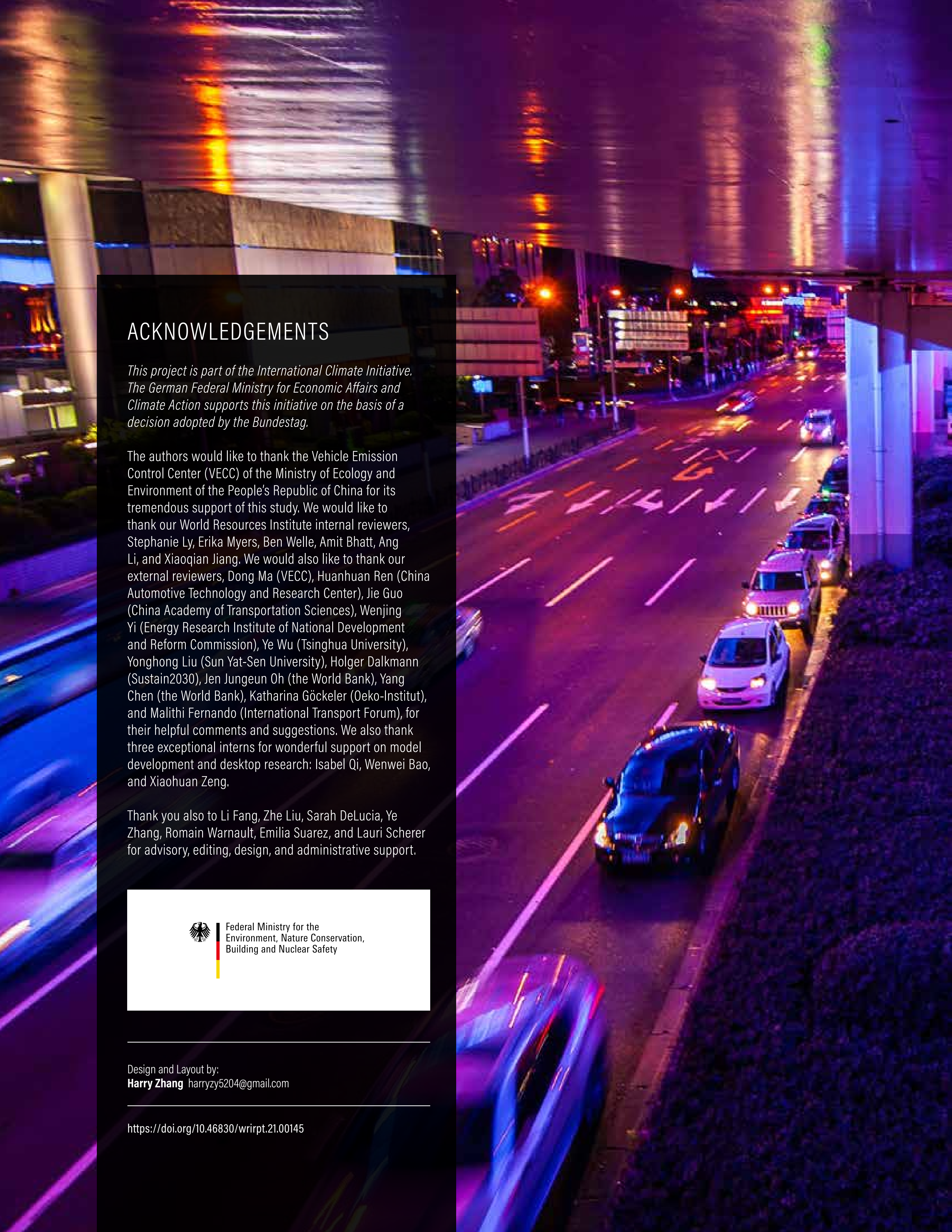


WRI CHINA

DECARBONIZING CHINA'S ROAD TRANSPORT SECTOR: STRATEGIES TOWARD CARBON NEUTRALITY

LULU XUE   DAIZONG LIU

WRI.ORG.CN



ACKNOWLEDGEMENTS

This project is part of the International Climate Initiative. The German Federal Ministry for Economic Affairs and Climate Action supports this initiative on the basis of a decision adopted by the Bundestag.

The authors would like to thank the Vehicle Emission Control Center (VECC) of the Ministry of Ecology and Environment of the People's Republic of China for its tremendous support of this study. We would like to thank our World Resources Institute internal reviewers, Stephanie Ly, Erika Myers, Ben Welle, Amit Bhatt, Ang Li, and Xiaoqian Jiang. We would also like to thank our external reviewers, Dong Ma (VECC), Huanhuan Ren (China Automotive Technology and Research Center), Jie Guo (China Academy of Transportation Sciences), Wenjing Yi (Energy Research Institute of National Development and Reform Commission), Ye Wu (Tsinghua University), Yonghong Liu (Sun Yat-Sen University), Holger Dalkmann (Sustain2030), Jen Jungeun Oh (the World Bank), Yang Chen (the World Bank), Katharina Göckeler (Oeko-Institut), and Malithi Fernando (International Transport Forum), for their helpful comments and suggestions. We also thank three exceptional interns for wonderful support on model development and desktop research: Isabel Qi, Wenwei Bao, and Xiaohuan Zeng.

Thank you also to Li Fang, Zhe Liu, Sarah DeLucia, Ye Zhang, Romain Warnault, Emilia Suarez, and Lauri Scherer for advisory, editing, design, and administrative support.

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

Design and Layout by:
Harry Zhang harryzy5204@gmail.com

https://doi.org/10.46830/wrirpt.21.00145

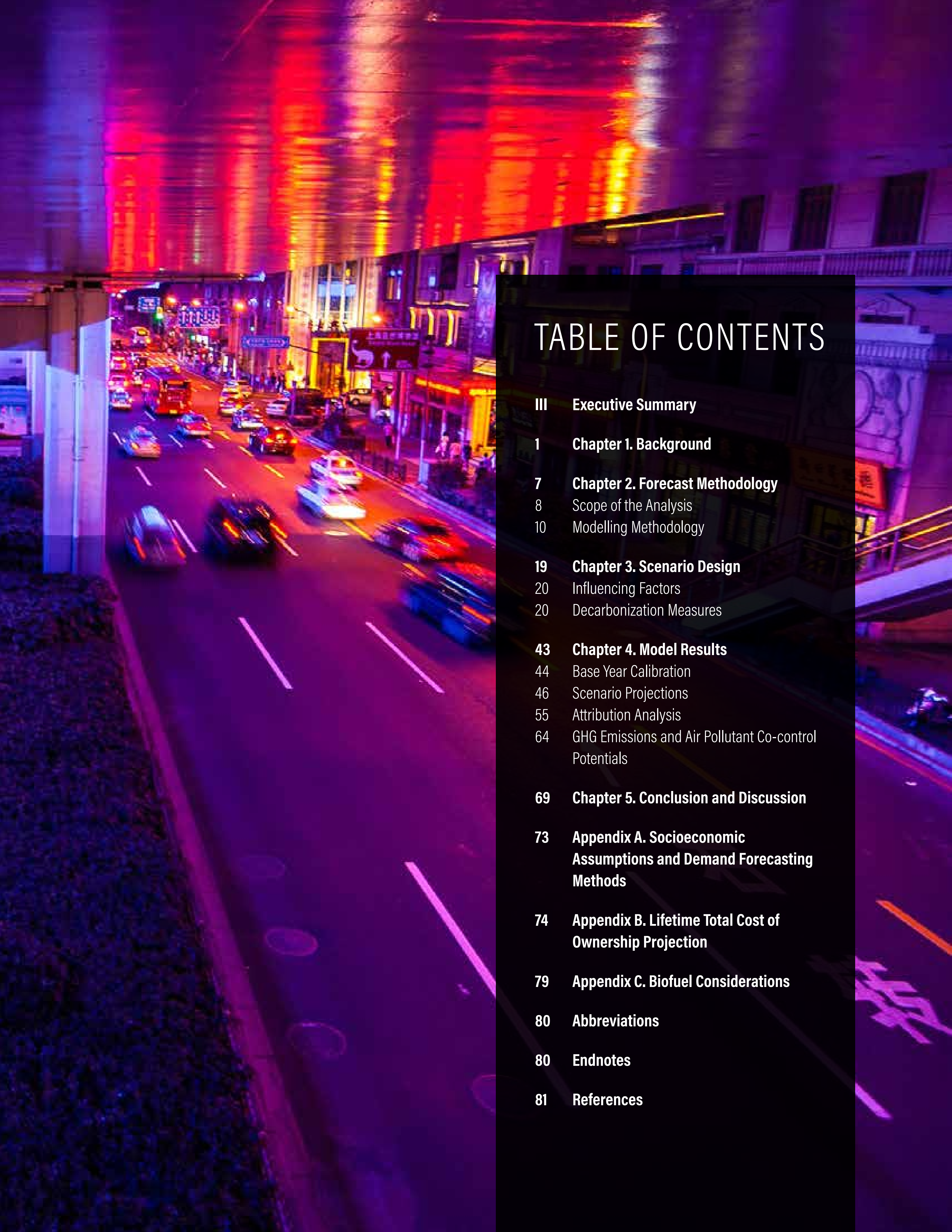
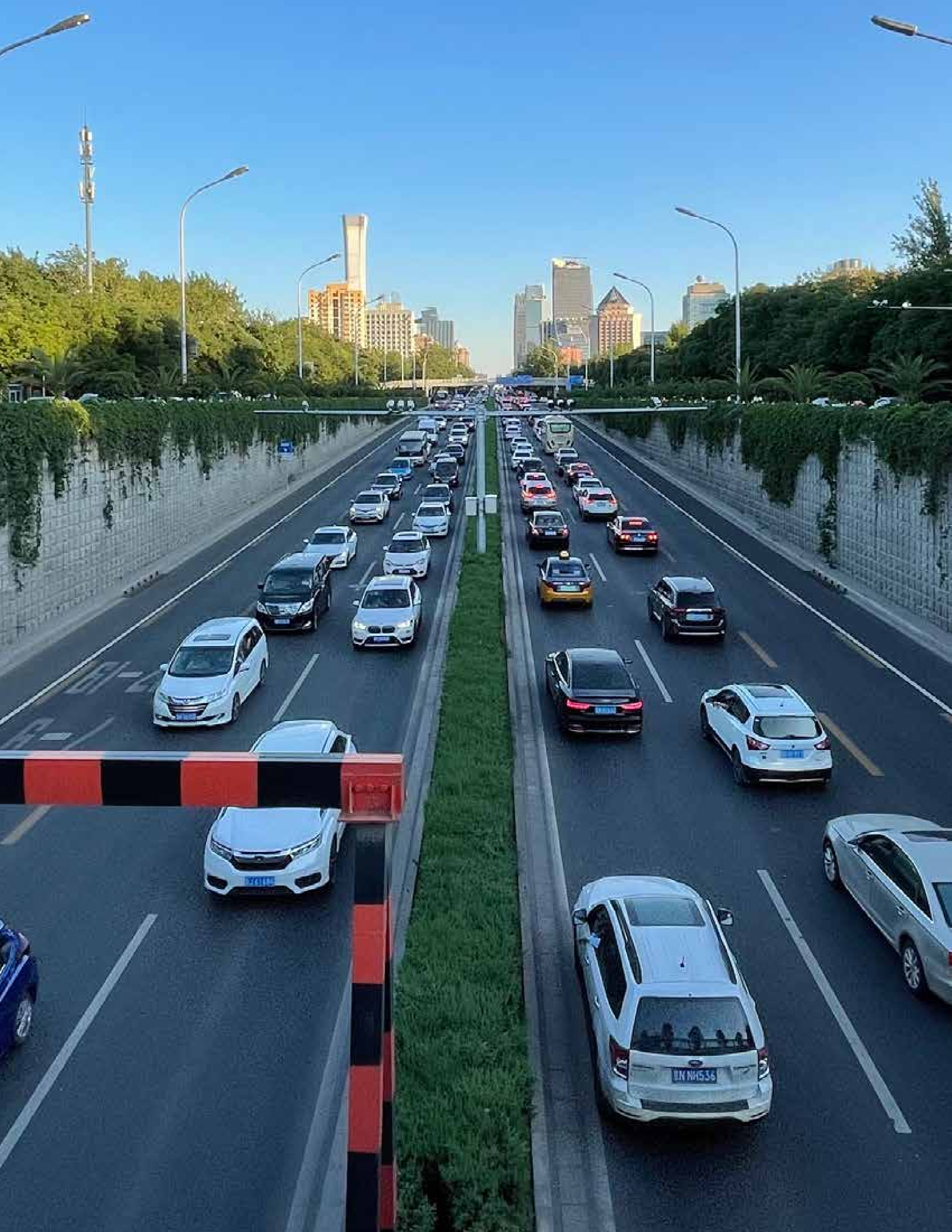


TABLE OF CONTENTS



EXECUTIVE SUMMARY

HIGHLIGHTS

- China's road transport greenhouse gas (GHG) emissions will continue growing. However, if China implements its stated policies, road transport emissions could peak before 2030 and petroleum consumption before 2027. The peaking timeline for GHG emissions could be further advanced to 2025 and that for petroleum consumption to 2024 if China takes more proactive structural change measures (including mode shift and vehicle occupancy improvements).

- If China implements all its stated policies, road transport's GHG emissions in 2060 would decline by 50 percent from the 2020 level. Further, if radical structural changes and vehicle electrification occur, road transport's GHG emissions in 2060 would reduce by 95 percent from 2020's level, fulfilling China's 2060 carbon neutrality commitment.

- Over the long term, vehicle electrification offers the largest decarbonization potential, followed by structural changes, fuel efficiency improvements, and the decarbonization of power and hydrogen generation sectors. However, structural changes have the largest decarbonization potential in the near term (from now until 2035).

- Public and private investments of 39–83 trillion Chinese yuan (CNY) cumulatively are needed from 2020 to 2060 to decarbonize China's road transport sector.

- Air pollutant emissions from China's road transport sector will decouple from GHG emission trajectories, demonstrating a steady declining trend.

Research Problem

Decarbonizing the transport sector globally is necessary to meet the Paris Climate Agreement goal of limiting warming to below 2 degrees Celsius (°C) or the more ambitious 1.5°C target. For China, doing so is also critical for meeting the country's goals of peaking carbon dioxide emissions before 2030 and being carbon neutral by 2060. Further, historical and projected trends for growth in China's road transport sector demand have raised concerns over national energy security and local air pollution.

At present, transport sectoral emission reduction targets and mitigation actions compatible with the carbon neutrality target have not yet been established. As indicated by the *Action Plan for Carbon Dioxide Peaking before 2030*, released by China's State Council on October 26, 2021, petroleum consumption from the road transport sector should peak before 2030, with a goal to "keep the growth of carbon emissions in the transportation domain within an appropriate range" (NDRC 2021). This indicates that China's transport emissions probably will not peak before 2030. However, existing modelling studies suggest that to meet the 2-degree (or 1.5-degree) goal, global transport emissions need to peak around 2020–25 (IEA 2021a; Gota et al. 2018; Fransen et al. 2019).

Within the transport sector, road transport represented the largest share—84.1 percent—of transport-related GHG emissions in China in 2014 (MEE 2020a). To meet its carbon neutrality goal, China's road transport sector needs explicit sectoral emission reduction targets, actionable strategies, and cost-effective policy instruments. This study examines how the sector might be decarbonized to inform the following:

- The road transport sector's target setting to help achieve China's carbon peaking and neutrality goals
- Identification of cost-effective measures that deliver on the sectoral emission reduction targets, facilitate low-carbon investments, and drive technological innovation
- Identification of decarbonization measures with air pollution reduction co-benefits

Using the Low Emissions Analysis Platform (LEAP) model, we constructed and analyzed the results of the following five forecasting scenarios (Table ES-1):

- The Business as Usual (BAU) scenario is a counterfactual scenario, representing no improvement in energy efficiency and limited degrees of vehicle electrification to help evaluate the emissions reduction potential of China's stated policies and the consequences of not meeting these targets.
- The Stated Policy scenario ("Stated_policy") is based on the stated policies announced by the national government and intended actions from industrial associations.
- The Structural Change scenario ("Low_stock") assumes greater degrees of transport structural changes (through two measures—mode shift and vehicle occupancy improvements), thereby featured by smaller vehicle stocks.
- The Deep Electrification scenario ("DeepELE") assumes more rapid diffusion of new energy vehicles[i] (NEVs), with NEV passenger cars representing 100 percent of passenger car sales by 2035 and NEV medium- and heavy-duty trucks (HDTs) representing 100 percent of HDT sales by 2050.
- The Deep Decarbonization scenario ("DeepDecarb") integrates the Low_stock and DeepELE scenarios. Therefore, the scenario represents the most ambitious case that is compatible with China's 2060 carbon neutrality target.

Table ES-1 | **Key Parameters in the Five Forecasting Scenarios**

	2020	BUSINESS AS USUAL (BAU)	STATED POLICY (Stated_policy)	STRUCTURAL CHANGE (Low_stock)	DEEP ELECTRIFICATION (DeepELE)	DEEP DECARBONIZATION (DeepDecarb)
Demand and Structural Change						
Passenger car stock in 2020 and 2060 (million vehicles)	239 (170 cars per 1,000 persons)	506 (425 cars per 1,000 persons)	506	381 (300 cars per 1,000 persons)	506	381
Freight tkm in 2020 and 2060 (trillion tkm)	11.2	25.9				
Freight mode share in 2020 and 2060 (% of road freight in domestic tkm)	54%	50%	50%	40%	50%	40%
Freight average load in 2020 and 2060 (tonnes per vehicle kilometer)	9.5	9.5	9.5	11.5	9.5	11.5
HDT stock in 2020 and 2060 (million vehicles)	9.5	20	20	12	20	12
Vehicle electrification						
Passenger car electrification in 2020 and 2035 (% of NEVs in passenger car sales)	15.7%	30%	50%	50%	100%	100%
HDT electrification in 2020 and 2050 (% of NEVs in HDT sales)	0.6%	12%	50% (only HDTs operating in urban deliveries, drayage, and regional delivery duty cycles)	50% (only HDTs operating in urban deliveries, drayage, and regional delivery duty cycles)	100% (all HDTs, including long-haul and refrigerated HDTs)	100% (all HDTs, including long-haul and refrigerated HDTs)
Fuel efficiency						
ICE passenger cars	Fleet average: 5.6 L/100 km Hybrid: 2.6% of car sales	No improvement	Fleet average: 4 L/100 km Hybrid: 60% of car sales in 2025, 100% in 2035			
ICE HDTs	*(Depends on gross vehicle weight)*	No improvement	HDTs: 20% improvement in 2035			
NEVs	*(Depends on gross vehicle weight)*	No improvement	(*Various degrees of improvement based on gross vehicle weight*)			
Grid and hydrogen decarbonization						
Power mix in 2020 and 2050 (% of non-fossil fuels in power mix)	32%	75%	92%			
Hydrogen mix in 2020 and 2050 (% of gray hydrogen in production mix)	99%	35%	15%			

Abbreviations: tkm = tonne-kilometer; HDT = heavy-duty truck; NEV = new energy vehicle; ICE = internal combustion engine; L = liter; km = kilometer.
Source: WRI authors' assumptions.

Research Findings

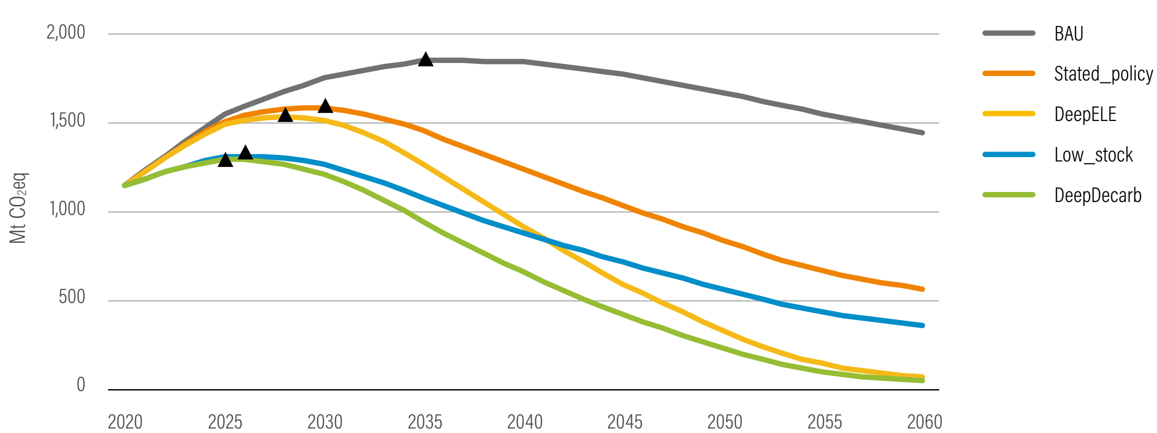
Our models indicate the following: First, road transport GHG emissions in China would peak during 2025–35, and petroleum demand would peak during 2024–30 under all scenarios except for Business as Usual. Driven by increasing travel demand, China's road transport GHG emissions would continue growing. Nonetheless, **if China implements its stated policies (the Stated_policy scenario), road transport emissions could peak before 2030 and petroleum consumption before 2027** (Figure ES-1). **The peaking timeline for GHG emissions would be advanced to 2025 and that for petroleum consumption to 2024 at the earliest if China takes more proactive structural change measures that include mode shifting to low-emitting modes as well as increasing vehicle occupancy** (DeepELE, Low_stock, and DeepDecarb scenarios). In the near term, structural changes are more effective at peaking emissions earlier and reducing emissions to a greater extent than vehicle electrification.

Second, over the long term, under different policy scenarios, the country can reduce road transport GHG emissions in 2060 by about 50–95 percent from the base year (2020). Specifically, **if China implements its stated policies, its road transport GHG emissions in 2060 would decline by 50 percent from 2020's level (the Stated_policy scenario). Further, if a radical shift in vehicle technologies and structural changes is made, road transport GHG emissions in 2060 would be reduced by 95 percent from the 2020 level, realizing China's 2060 carbon neutrality commitment** (the DeepDecarb scenario) (Figure ES-1).

To achieve the largest emission reduction potential of 95 percent by 2060 in the DeepDecarb scenario, four measures—namely, vehicle electrification, structural changes, fuel efficiency improvements, and power and hydrogen decarbonization—are critical (Figure ES-2 and Table ES-2):

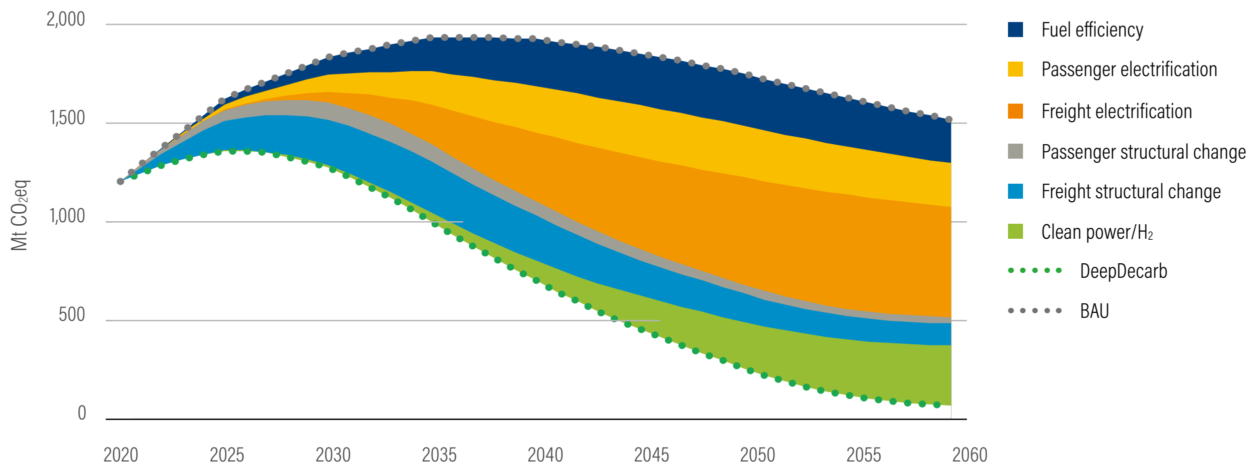
- **Vehicle electrification has the largest decarbonization potential, contributing 48 percent of the cumulative GHG emission reduction** from the BAU scenario to the DeepDecarb scenario during 2020–60. If the decarbonization of the power and hydrogen-related sectors follows the roadmaps outlined by the national government and industrial associations, vehicle electrification could yield a cumulative 60 percent emission reduction.
- **Structural changes have the second-largest mitigation potential and can cut cumulative GHG emissions from 2020 to 2060 by 23 percent. Of note, in the near term (2020–35), structural changes have the largest mitigation potential** because vehicle electrification is not likely to reach the tipping point during this time frame.

Figure ES-1 | GHG Emission Projections under Different Scenarios



Note: Greenhouse gases include carbon dioxide, nitrous oxide (N_2O), and methane (CH_4). N_2O and CH_4 use 20-year global warming potential (GWP) values from IPCC (2014).
Abbreviation: Mt CO_2eq = million tonnes of carbon dioxide equivalent.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Figure ES-2 | **GHG Reduction Potentials of Key Decarbonization Interventions**



Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; DeepDecarb = Deep Decarbonization scenario; H_2 = hydrogen; BAU = Business as Usual scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

- **Fuel efficiency improvements can generate 17 percent of the cumulative emission reduction during 2020–60.** Further, tightening the fleet-wide fuel efficiency standard is instrumental to stimulating NEV production, while NEV energy efficiency improvements help improve NEVs' driving ranges as well as reduce vehicle weights and costs.

Whether natural gas (NG) vehicles should be treated as a viable decarbonization solution is worth further scrutiny. Although the carbon dioxide (CO_2) emissions from NG vehicles are around 20 percent lower than those of diesel- and gasoline-powered vehicles, they have limited GHG emissions savings due to methane escape from NG vehicles (such as crankcase emissions or dynamic venting of the fuel system). This study shows that because of large methane leakage, an NG heavy-duty truck meeting the China 5 emission standard would tend to have higher tank-to-wheel GHG emissions than its diesel counterpart. Only when the China 6 emission standard is stringently enforced would a China 6 NG heavy-duty truck reduce tank-to-wheel GHG emissions by up to 12 percent. In the scenario analysis, when the market share of China 6 NG heavy-duty trucks rises to 50 percent in 2050 in the Stated_policy scenario (compared with the original 15 percent), the wider adoption of NG trucks would lead to an additional 7 percent GHG emission reduction in 2060 and less than a 3 percent cumulative GHG emission reduction from 2020 to 2060, compared with the Stated_policy scenario.

This study further reveals that for China to achieve its carbon neutrality goal, **its stated policies need to include increased ambition on structural changes and vehicle electrification** (Table ES-2):

- For structural changes, a 75–85 percent green transport mode share for passenger transport, 40 percent road freight in the mode split for domestic tonne-kilometers (tkm), and an average 11.5 tonne load per truck-kilometer

- For vehicle electrification, NEVs would represent 100 percent of passenger car sales by 2035 and 100 percent of HDT sales by 2050

Reaching China's carbon neutrality target has more pronounced implications for freight transport than it does for passenger transport. The DeepDecarb scenario shows that road freight transport could reduce GHG emissions by a cumulative 19,367 million tonnes of carbon dioxide equivalent (Mt CO_2eq) from 2020 to 2060 compared with the BAU scenario, over two times the cumulative emission reduction associated with road passenger transport (9,250 Mt CO_2eq). To unlock road freight's decarbonization potential, China needs to make technology advances in long-haul HDTs and refrigerated HDTs, promote freight mode shifts to railways and waterways, and improve freight logistic efficiency. China also needs to significantly improve its freight statistical data

Table ES-2 | **Key Targets and Policy Interventions to Realize the Carbon Neutrality Commitment**

	STRUCTURAL CHANGES	VEHICLE ELECTRIFICATION	FUEL EFFICIENCY IMPROVEMENTS	POWER AND HYDROGEN DECARBONIZATION
Targets in the Stated_policy scenario				
Passenger transport	***Targets:*** 425 cars per 1,000 persons, 70% green transport mode share in 2060[a]	***Targets:*** By 2035: NEVs represent 50% of passenger car sales[b] By 2060: NEVs represent 100% of car sales[c]	***Targets:*** By 2025: Fleet-average fuel consumption for passenger cars of 4 L/100 km; hybrid vehicles represent 60% of passenger car sales (100% in 2035)[d] By 2025: NEVs' energy efficiency of 12 kWh/100 km[e]	***Targets:*** By 2050: 92% of non-fossil fuel in power mix[f]
Freight transport	***Targets:*** 50% of road freight in domestic tkm; average load: 9.5 tonnes per vehicle-kilometer[g]	***Targets:*** By 2050: NEVs represent 50% of HDT sales (that is, the HDTs operating in urban deliveries, drayage, and regional delivery duty cycles)[h]	***Targets:*** By 2035: 20% improvement in HDTs' fuel consumption[i] Continuous improvement in NEVs' energy efficiency	***Targets:*** By 2050: 15% of gray hydrogen in production mix[j]
Targets and policies in the DeepDecarb scenario				
Passenger transport	***Targets:*** 300 cars per 1,000 persons, 75–85% green transport mode share in 2060	***Targets:*** NEVs represent 100% of passenger car sales in 2035	Same targets as the Stated_policy scenario	Same targets as the Stated_policy scenario
	Tactics: • Shift transit service paradigm with intelligent demand responsive services • Increase the share of infrastructure investments in transit, active mobility, and railway • Pursue travel demand management and carbon pricing • Promote Mobility-as-a-Service and ride sharing	***Tactics:*** • Enhance fleet-wide fuel consumption standard • Provide road access privileges to NEVs • Increase infrastructure accessibility • Introduce carbon taxes		
Freight transport	***Targets:*** 40% of road freight in domestic tkm; average load = 11.5 tonnes per HDT vehicle-kilometer	***Targets:*** NEVs represent 100% of HDT sales in 2050 (HDTs for short-range and long-range duty cycles)	Same targets as the Stated_policy scenario	Same targets as the Stated_policy scenario
	Tactics: • Shift bulk commodities to railways and waterways and promote intermodal freight for high-value freight • Invest in intermodal infrastructure and equipment, improve service connectivity, rationalize pricing and scheduling, and enhance first-/last-mile truck delivery • Encourage the use of non-truck operating carriers and facilitate drop-and-hook operations • Employ fuel taxes and road charges	***Tactics:*** • Increase vehicle acquisition and introduce operation subsidies • Introduce fleet-wide fuel consumption standard for HDTs • Introduce CO_2-emission indexed road pricing • Provide road access privileges • Increase infrastructure accessibility		

Note: a. Extrapolated by the authors based on NDRC (2021). b. China SAE 2020. c. Extrapolated by the authors. d. MIIT 2019, 2021; China SAE 2020. e. State Council 2020. f. ICCSD 2020. g. Extrapolated by the authors based on NDRC (2021). h. Extrapolated by the authors. i. China SAE 2020. j. CHA 2019.

collection system to support evidence-based policymaking in the above areas.

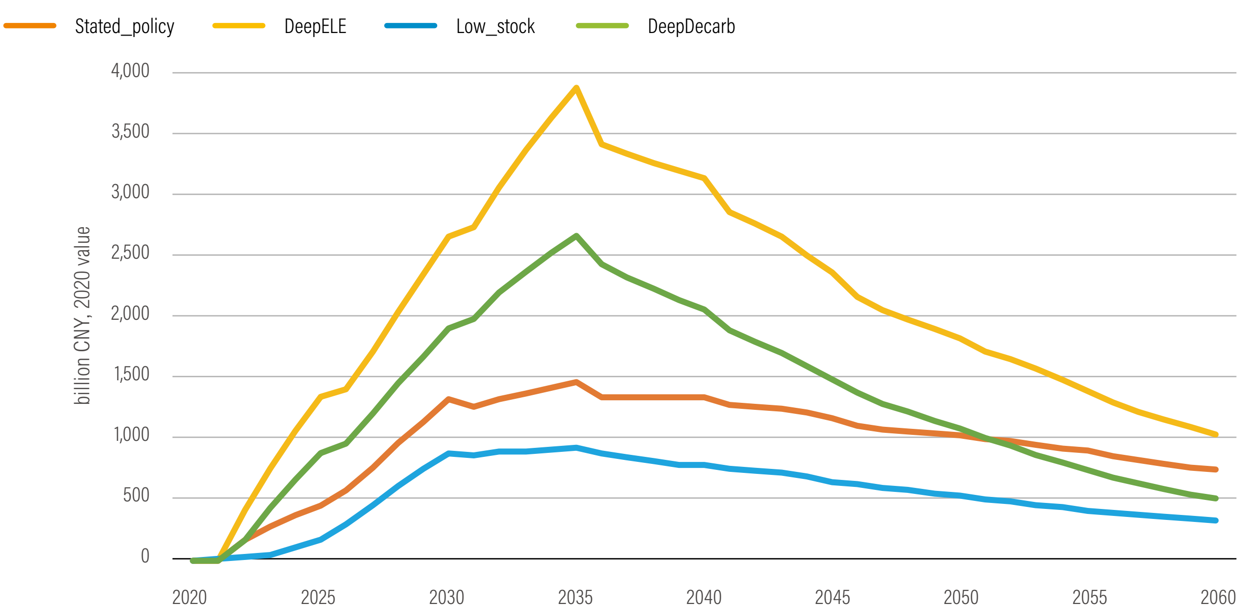
The results show that **low-carbon investments amounting to 39–83 trillion CNY cumulatively are needed from 2020 to 2060 to decarbonize China's road transport sector.** The investment demand is the largest from now till 2035 and will steadily decline over time. Among all the scenarios, **the Low_stock scenario is the lowest-cost pathway**, with an average abatement cost of 675 CNY per tonne of CO_2eq reduced thanks to an associated smaller vehicle fleet (Figure ES-3).

Structural changes are the least-expensive measure among all the decarbonization measures because a smaller vehicle fleet size reduces needed investments in installed capacities for power and hydrogen generation and transmission as well as investments in vehicle acquisition and charging (and refueling) infrastructure expansion.

Vehicle electrification's abatement costs vary significantly over time. Only after the total cost of ownership parity for NEV heavy-duty trucks is reached (around 2030–35) will NEVs exhibit net cost savings compared with internal combustion engine (ICE) vehicles. However, the high abatement costs of vehicle electrification should not deter relevant investments.

After the introduction of the China 6 emission standard[ii] (hereafter referred to as the China 6 standard), **road transport's air pollutant emissions would decouple from GHG emissions trajectories,** showing a steady

Figure ES-3 | **Low-Carbon Investments (2020-60) under Different Scenarios**

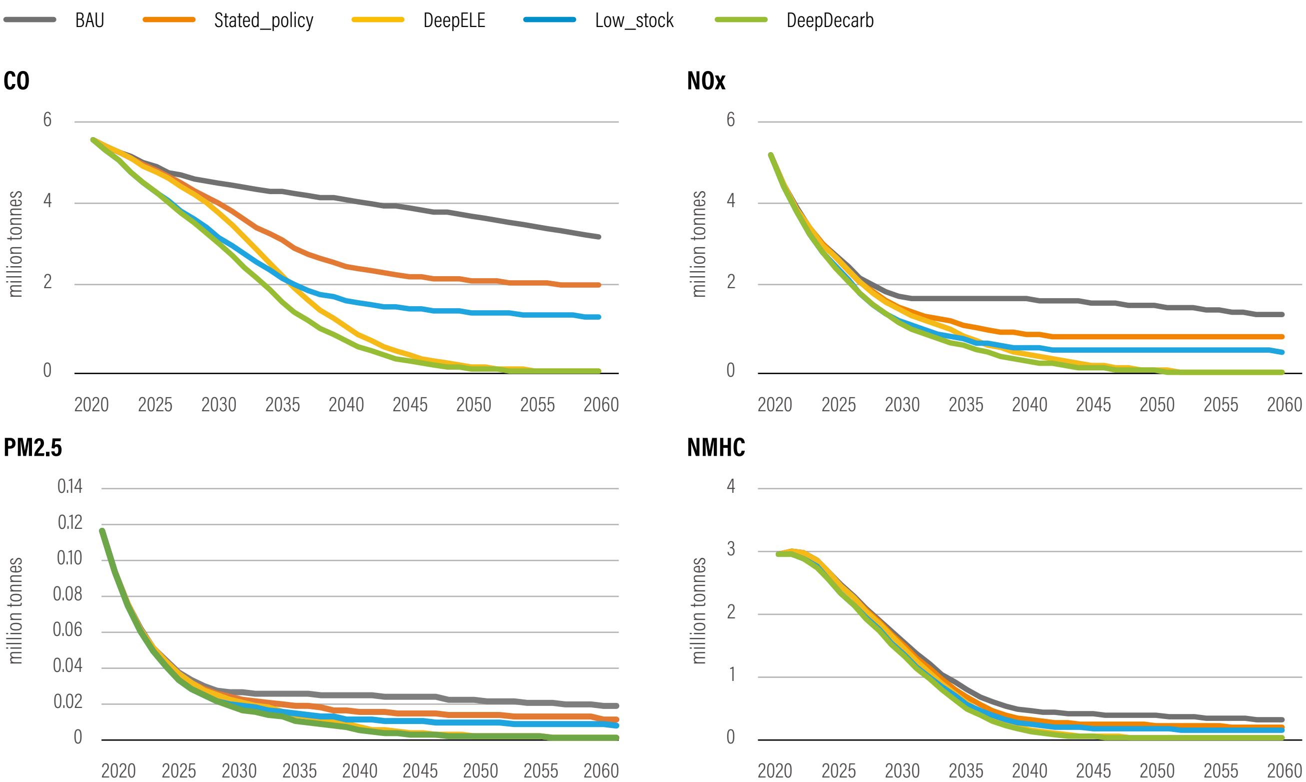


	Stated_policy	DeepELE	Low_stock	DeepDecarb
Cumulative low-carbon investments (billion CNY, 2020 value)	39,503	83,896	22,070	54,226
Average abatement cost (CNY per tonne of CO_2eq reduced)	1,852	2,510	675	1,331

Abbreviations: CNY = Chinese yuan; CO_2eq = carbon dioxide equivalent; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

declining trend (Figure ES-4). **Despite this achievement, air pollution abatement efforts should be sustained** because non-road transport sectors such as inland waterways and non-road machinery also contribute significant amounts of air pollutants, and the next-generation China exhaust emission standard (such as a Euro 7 equivalent standard) would be conducive to accelerating NEV adoption. This study further shows that for the aforementioned decarbonization measures to produce air pollution reduction co-benefits, additional measures are necessary, including improving railways and waterways' freight operational efficiency, promoting railway electrification, tightening the China 6 standard, and improving in-use vehicles' inspection/maintenance programs (Table ES-3).

Figure ES-4 | **Air Pollutant Emissions from the Road Transport Sector**



Abbreviations: CO = carbon monoxide; NOx = nitrogen oxides; PM2.5 = particulate matter 2.5 micrometers or less in diameter; NMHC = non-methane hydrocarbons.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Table ES-3 | **The Co-control Effects of Different Decarbonization Measures**

	RESEARCH	CO-CONTROL EFFECTS	POLICY IMPLICATIONS
Fuel efficiency standards	This study	🟡 **General fuel efficiency measures:** Reduce GHG emissions, neutral to air pollutants	--
	O'Driscoll et al. 2018	🟢 **Hybrid (gasoline) vehicles:** Reduce GHG emissions and air pollutants	Promote hybrid (gasoline) vehicles
	Liang et al. 2012 Saliba et al. 2017 O'Driscoll et al. 2018	🟡 **Gasoline direct injection:** Reduce GHG emissions but increase air pollutants	Enforce China 6 standard and enhance inspection/ maintenance programs for in-use vehicles
NG vehicle promotion	This study Mottschall et al. 2020 T&E 2020a	🟡 **NG vehicles:** Possibly increase GHG emissions, reduce/ neutral to air pollutants	Tighten China 6 standard on non-tailpipe CH_4 emissions from NG vehicles, enhance inspection/ maintenance programs
NEV promotion	This study	🟢 **NEV promotion:** Reduce GHG emissions and air pollutants	--
	Peng et al. 2021	🟡 **NEVs and upstream emissions:** Reduce GHG emissions, increase upstream air pollutants	Couple NEV promotion with the decarbonization of the upstream power and industrial sector
Passenger structural changes	This study	🟢 **Passenger structural changes:** Reduce GHG emissions and air pollutants	--
Freight structural changes	This study	🟢 **Freight structural changes:** Reduce GHG emissions and air pollutants	--
	Shao 2020	🟡 **Freight structural changes (mode shift to railways):** Reduce GHG emissions, increase upstream air pollutants	Decarbonize the upstream power sector, promote railway electrification, and reduce railway backhauls

Note: Green cells 🟢 indicate that the measure can reduce both GHG emissions and air pollutants, and yellow cells 🟡 mean that the measure can reduce only GHG/ air pollutant emissions.
Abbreviations: GHG = greenhouse gas; CH_4 = methane; NG = natural gas; NEV = new energy vehicle.
Source: WRI authors, based on this study and existing literature.


充电车位

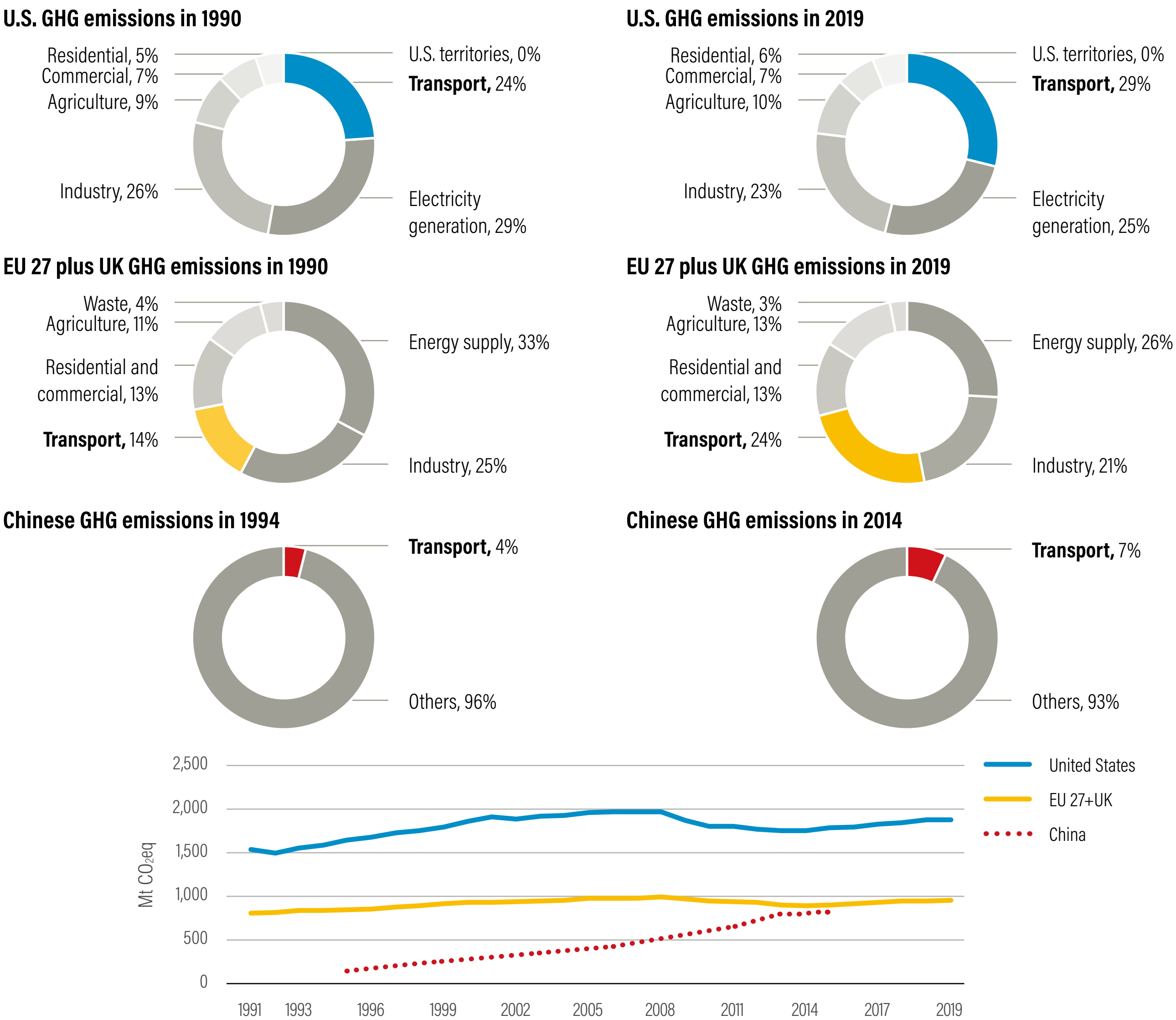
CHAPTER 1

BACKGROUND

Decarbonizing the transport sector globally is necessary to meet the Paris Climate Agreement goal of limiting warming to below 2 degrees Celsius (°C) or the more ambitious 1.5°C target. For China, doing so is also critical for meeting the country's goals of peaking carbon dioxide emissions before 2030 and being carbon neutral by 2060.

In China, transport sector greenhouse gas (GHG) emissions equated to 828 million tonnes of carbon dioxide equivalent (Mt CO_2eq) in 2014, representing 6.7 percent of the country's GHG emissions, excluding land use, land-use change, and forestry (LULUCF) emissions (MEE 2018a). However, if the sectoral emissions continue their upward growth trend, this share will enlarge. In fact, even in the developed world, such as the 27 members of the European Union (EU 27) plus the United Kingdom (UK) and the United States, transport-related GHG emissions have been increasing since 1990, in contrast to the general decreasing emissions trends in the power and industrial sectors. In 2019, the transport sector accounted for 28.6 percent and 23.6 percent of total GHG emissions (excluding LULUCF emissions) in the United States and EU, respectively, rising to become the largest emitter in the United States and second-largest emitter in the EU (EEA 2020; EPA 2020) (Figure 1).

Figure 1 | **Transport Emissions Growth Trajectories and the Shares of Transport Emissions in Total Greenhouse Gas Emissions (excluding LULUCF) in the United States, EU 27 plus UK, and China**



Note: The most recent official record of China's transport GHG emissions is from 2014—the country needs to improve the frequency of its national GHG emission reporting to keep pace with the rapid growth in emissions. China's emission trajectory is a linear extrapolation of the emission data points in 1994, 2005, 2010, 2012, and 2014.
Abbreviations: GHG = greenhouse gas; LULUCF = land use, land-use change and forestry; EU 27 = the 27 members of the European Union; UK = United Kingdom; Mt CO_2eq = million tonnes of carbon dioxide equivalent.
Sources: EPA 2020; EEA 2020; NDRC 2004, 2012, 2016; MEE 2018a, 2018b.

China's transport GHG emissions contribute significantly to global transport GHG emissions. They accounted for 11.1 percent of the world's transport GHG emissions in 2018 (Climate Watch 2020), following only the United States (21.3 percent) and EU 27 plus UK (11.2 percent). In the future, China's transport sector's global contribution could be even greater: It is projected that China will have the most road freight activities in the world by 2050 (Mulholland et al. 2018) and that China and India combined will experience the most rapid growth in car ownership, six times greater than in 2015, standing in contrast to 16 percent growth in Organisation for Economic Co-operation and Development (OECD) countries (ITF 2019). Historical and projected growth trends for travel demand in China's road transport sector have raised concerns over national energy security, local air pollution, and GHG emissions (Yin et al. 2015; Hao et al. 2015).

Within the transport sector, mitigating road transport emissions is critical to achieving China's 2060 carbon neutrality target. In 2014, GHG emissions from road transport represented 84.1 percent of China's transport-related GHG emissions. Further, unlike aviation and maritime shipping where decarbonization efforts are hindered by immature technologies and high abatement costs, major technology breakthroughs such as electric powertrains and hydrogen fuel cells already exist for road transport (BloombergNEF 2021).

In China, sectoral emission reduction targets and decarbonization strategies compatible with the carbon neutrality target have not yet been established. As indicated by the *Action Plan for Carbon Dioxide Peaking before 2030*, released by China's State Council on October 26, 2021, petroleum consumption from the road transport sector should peak before 2030, with a goal to "keep the growth of carbon emissions in the transportation domain within an appropriate range" (NDRC 2021). This indicates that Chinese transport emissions probably will not peak before 2030. However, existing modelling studies suggest that to meet the 2°C (or more ambitious 1.5°C) target, global transport emissions need to peak around 2020–25 (IEA 2021a; Gota et al. 2018; Fransen et al. 2019). To that end, China's road transport sector needs explicit sectoral emission-reduction targets, actionable strategies, and cost-effective policy instruments. Therefore, this study aims to inform the following:

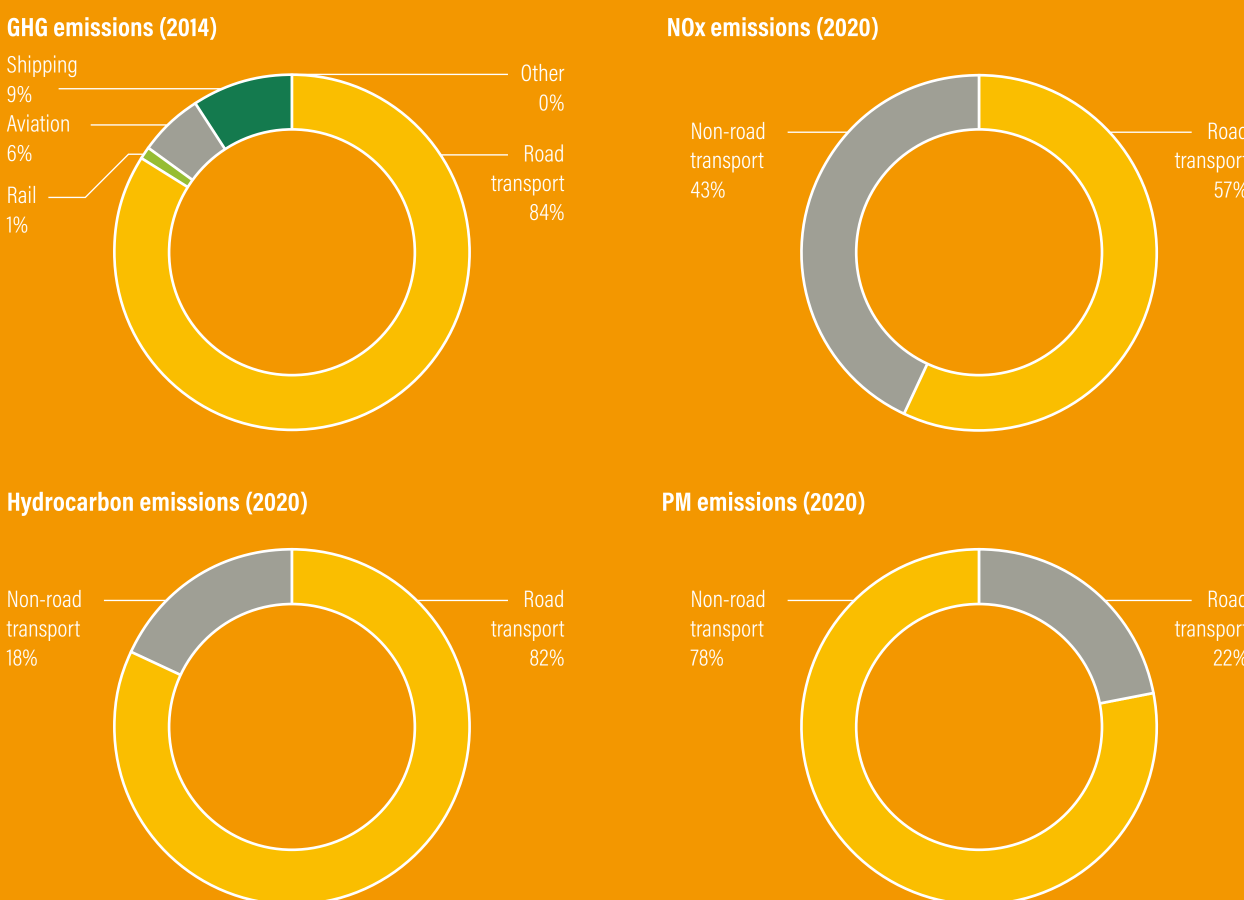
- The road transport sector's target setting to help achieve China's carbon peaking and neutrality targets
- Identification of cost-effective measures that deliver on the sectoral target, facilitate low-carbon investments, and drive technology innovation
- Identification of decarbonization measures with air pollution reduction co-benefits (see Box 1).

Box 1 | Transport-Related Air Pollutant Emissions in China

The transport sector is a major contributor to air pollution in China, accounting for about 20–50 percent of emissions of particulate matter 2.5 micrometers or less in diameter (PM2.5) in Chinese cities; in some cities such as Shenzhen, Beijing, and Guangzhou, the transport sector is the largest source of PM2.5 emissions, representing 52 percent, 45 percent, and 22 percent of local PM2.5 emissions in those cities, respectively.[a]

Although unlike GHG emissions, road transport does not dominate air pollutant emissions, it emits more hydrocarbons (HC) and nitrogen oxides (NOx) than the non-road transport sectors do.

Figure B1.1 | **Emissions from the Road and Non-road Transport Sectors**



Note: The non-road transport sector includes the domestic shipping, domestic aviation, and non-road machinery sectors.
Abbreviations: GHG = greenhouse gas; NOx = nitrogen oxides; PM = particulate matter.
Source: MEE 2018a, 2021.

Box Notes: [a] MEE 2018c.

Box 1 | Transport-Related Air Pollutant Emissions in China (Cont.)

Since China rolled out its *Three-Year Action Plan to Win the Blue-Sky Defence Battle* in 2018, road transport–related air pollutants have been dropping (see Figure B1.2).[b] For annual concentrations of air pollutants to meet the National Ambient Air Quality Standard, the country has taken decisive actions, including introducing a China 6 emission standard, promoting the adoption of new energy vehicles, improving fuel quality, and facilitating the freight mode shift from roadways to railways and waterways. However, these measures have not corresponded to a commensurate impact on decarbonization—although road transport–related air pollutant emissions have begun to decline, GHG emissions are still growing (Figure B1.2).

As China increases its public investments to curb environmental degradation and improve air quality (from 880.6 billion CNY in 2015 to 1,063.9 billion CNY in 2020), the cost effectiveness of the investments could be improved.[c] At present, the Ministry of Ecology and Environment is responsible for reducing pollution, while the National Development and Reform Commission is tasked with reducing carbon dioxide emissions. The counterbalancing effects between decarbonization measures and pollution reduction measures can be overcome through interdepartmental coordination and coordinated policymaking.

Figure B1.2 | Annual Air Pollutant Emissions from China's Road Transport Sector (2011–20)

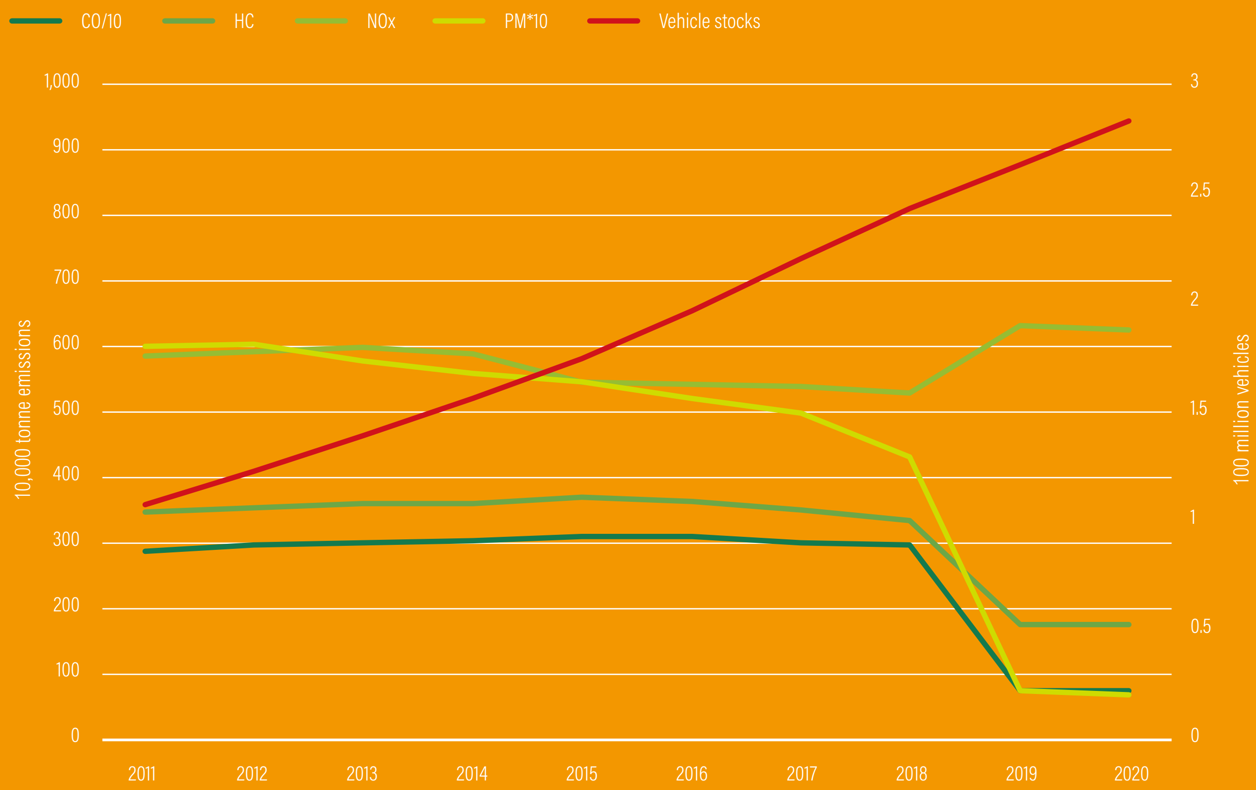


Figure Notes: The sudden shifts in pollutants in 2019 were due to changes in pollutant accounting methods and updates to emission surveys.
Figure Abbreviations: CO/10 = CO emissions divided by 10; HC = hydrocarbon; NOx = nitrogen oxides; PM*10 = particulate matter times 10.
Figure Sources: MEE 2011, 2012, 2013, 2014a, 2015, 2016, 2017, 2018c, 2019, 2020a, 2021; NBS 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021.

Box Notes: [b] MEE 2018d. [c] NBS 2017, 2020.

CHAPTER 2

FORECAST METHODOLOGY

This study examines how China's road transport sector might be decarbonized by modelling five scenarios using the Low Emissions Analysis Platform (LEAP) model. This chapter describes the vehicle classification, the emission scopes, and the methods used for transport emission accounting and abatement cost estimation.

2.1 Scope of the Analysis

In this study, the road transport sector includes passenger carriers, goods carriers, and motorcycles. Non-road transport sectors such as aviation, shipping, pipelines, and off-road machinery are not covered.

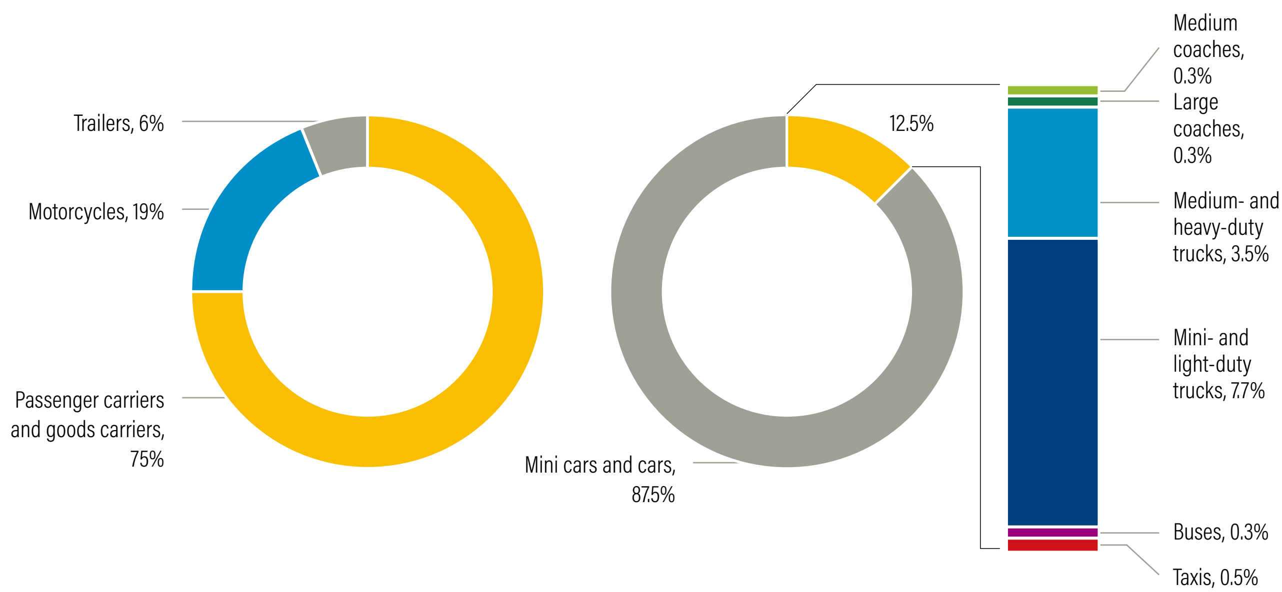
Table 1 provides an overview of China-specific vehicle classification. Given different activity levels and driving cycles, buses and taxies are separated from "large coaches" and "cars" as independent classes. The distribution of various vehicle types in 2020 is shown in Figure 2.

Table 1 | **Vehicle Classification Based on the Standard on Road Traffic Management—Types of Motor Vehicles (GA802-2019)**

CLASS		DESCRIPTION	THIS STUDY
Passenger carriers	Large coaches	Automobiles used to transport more than 20 people (vehicle length above 6 meters).	✓
	Medium coaches	Automobiles used to transport 10 to 19 people (vehicle length below 6 meters).	✓
	Cars	Automobiles used to transport 9 people or fewer (vehicle length above 3.5 meters and below 6 meters).	✓
	Mini cars	Automobiles used to transport 9 people or fewer (vehicle length of no more than 3.5 meters and engine cylinder capacity of no more than 1 liter).	✓
Goods carriers	Heavy-duty trucks	GVW over 12 tonnes and below 49 tonnes	✓
	Medium-duty trucks	GVW above 4.5 tonnes and below 12 tonnes	✓
	Light-duty trucks	GVW above 1.8 tonnes and below 4.5 tonnes	✓
	Mini-duty trucks	GVW below 1.8 tonnes	✓
Other carriers	Special purpose vehicles	Special purpose vehicles such as street-sweeping vehicles, cranes, cement mixer trucks, and refuse haulers, with the exclusion of those used for passengers or goods shipments	
	Low-speed vehicles	Three- or four-wheelers with a maximum speed of no higher than 70 km per hour	
Motorcycles	Motorcycles	Motorcycles powered by fossil fuels or electricity with a max speed over 25 km per hour	✓
Trailers	Trailers	Trailers are unpowered vehicles, designed for carrying goods	

Abbreviations: GVW = gross vehicle weight; km = kilometer.
Source: MPS 2019.

Figure 2 | **Distribution of Vehicle Types in China in 2020**



Note: According to the China Bicycle Association, China has 0.3 billion motorcycles (including e-scooters) (*Xinhua News* 2020)—a larger fleet size than passenger cars. However, because many motorcycles are unregistered, research relying on official statistics, which count only 68 million, would underrepresent motorcycles.
Sources: NBS 2021.

The scope of GHG emissions in this study includes well-to-wheel (WTW) emissions—including well-to-tank (WTT) emissions, especially from electricity/hydrogen generation—and tank-to-wheel (TTW) emissions from vehicle operations. Although this approach differs from the Intergovernmental Panel on Climate Change's (IPCC's) guidelines on national GHG inventories (IPCC 2006) where transport's WTT emissions are counted toward the power and industrial sectors (and NEVs[iii] count as zero emissions), our approach enables us to evaluate whether the large-scale adoption of NEVs could actually cut emissions. Further, the emissions from the production and maintenance of vehicles and construction and maintenance of infrastructure are not included.

The GHG emissions covered in this study include CO_2, methane (CH_4), and nitrous oxide (N_2O).

- CO_2 is primarily released through fuel combustion and upstream electricity/hydrogen generation. Since it represents the largest share of transport-related GHG emissions, it falls within the scope of this study.

- CH_4 is emitted via fuel combustion from motor vehicles and methane leaked from natural gas (NG) vehicles (Mottschall et al. 2020). Recent research shows that for lean burn NG vehicles—a type of engine common in China that relies on a high air-to-fuel ratio—methane leakage is considerable: The CH_4 emission factor for China 5 NG vehicles is eight times higher than the IPCC's default value (Pan et al. 2020). As NG vehicles are widely used in China, we included CH_4 emissions in this study.

- N_2O is emitted via fuel combustion and after-retreatment of exhaust gases. In particular, higher emissions of N_2O are found in diesel vehicles in compliance with higher emission standards such as China 5 and China 6. This is because the use of advanced aftertreatment systems to reduce NOx emissions leads to increased N_2O emissions (Clairotte et al. 2020). With the roll-out of the China 6 emission standard, N_2O emissions are likely to increase and so are included in this study.

- Hydrofluorocarbons (HFCs) such as HFC-134a (1,1,1,2-tetrafluoroethane) result from leaks and the end-of-life disposal of air conditioners used in vehicles (EPA 2015). Although HFC-134a has a low ozone-depleting potential, its global warming potential (GWP) is large. But due to limited data availability, we did not include HFC emissions in this study.

Air pollutants in this study include only TTW emissions since the major health impact from transport air pollutants is on the tailpipe side (TTW). In this study, TTW emissions include exhaust emissions and evaporative emissions; tire and brake wear emissions are not covered due to a lack of localized emission factors (Table 2).

The air pollutants considered in this study are the pollutants regulated in the China 1–6 vehicle emissions standards including carbon monoxide (CO), nitrogen oxides (NOx), non-methane hydrocarbons (NMHC), CH_4, N_2O, fine particulate matter (PM2.5), and coarse particulate matter (PM10, particulate matter 10 micrometers or less in diameter). Notably, there are overlaps between air pollutants and GHG emissions. For example, PM10 also includes black carbon, a type of short-lived climate pollutant with significant GWP, while GHG emissions like CH_4 and N_2O are also air pollutants. For simplicity, the GHG emissions in this study include only CO_2, CH_4, and N_2O (hence, CH_4 and N_2O are not treated as air pollutants).

2.2 Modelling Methodology

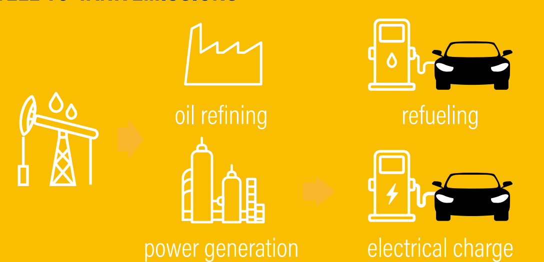
2.2.1 Emissions accounting and forecasting

We modelled current and future GHG and air pollutant emissions mostly using the Low Emissions Analysis Platform (LEAP) (Heaps 2022). As an integrated assessment model, LEAP can capture the interactions between supply sectors (e.g., power) and demand sectors (e.g., transport), such as the impact of energy demand on energy prices (Yeh et al. 2017). For simplicity, this study focuses on the transport sector alone, without endogenous interactions with supply sectors.

To estimate base-year GHG emissions, we used the bottom-up method in LEAP (Equation 1). To estimate air pollutants, we used MEE (2014b) to

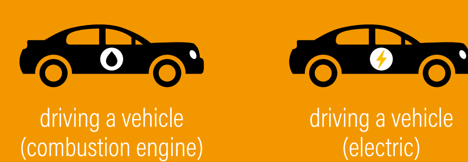
Table 2 | **The Scopes of Greenhouse Gas and Air Pollutant Emissions in This Study**

WELL-TO-TANK EMISSIONS



	TYPES OF WTT EMISSIONS	THIS STUDY
GHG emissions	· Emissions from raw material extraction (and/or land use changes)	
	· Emissions from oil refineries[a]	✓
	· Emissions from electricity/hydrogen generation	✓
Air pollutants	· Emissions from raw material extraction (and/or land use changes)	
	· Emissions from oil refineries and electricity/hydrogen generation	

TANK-TO-WHEEL EMISSIONS



	TYPES OF WTT EMISSIONS	THIS STUDY
GHG emissions	· Fuel combustion emissions	✓
	· Methane leakage emissions	✓
	· Emissions from urea-based catalytic converters[b]	
Air pollutants	· Fuel combustion emissions	✓
	· Evaporative emissions[c]	✓
	· Tire and brake wear emissions	

Notes: [a] Emissions were calculated but not analyzed in-depth for decarbonization measures.
[b] Carbon dioxide emissions from urea consumption in the selective catalytic reduction system—a type of pollutant aftertreatment device to reduce nitrogen oxides—are not considered due to limited emissions.
[c] Evaporative emissions include hot soak, diurnal, and running loss emissions; refueling emissions are not accounted for.
Abbreviations: WTT = well to tank; TTW = tank to wheel; GHG = greenhouse gas.
Sources: Text: WRI authors. Graphics: HPK 2019.

calculate both exhaust emissions (Equation 2) and evaporative emissions (Equation 3).

- For CO_2 emissions:

$$E=\sum_i^N P_i \times FE_i \times VKT_i \times EF_i \qquad \text{(Equation 1)}$$

where,
E represents CO_2 emissions (kilograms; kg)
P_i is the vehicle stock of vehicle segment i (number of vehicles)
FE_i is the fleet-average fuel efficiency of vehicle segment i (in liters per 100 kilometers [L/100 km] for diesel and gasoline, megajoules per 100 kilometers [MJ/100 km] for natural gas, kilowatt-hours per 100 kilometers [kWh/100 km] for electricity, and kilograms per 100 kilometers [kg/100 km] for hydrogen)
VKT_i is the average annual vehicle kilometers travelled of vehicle segment i (km)
EF_i is the CO_2 emission factor of different energies (kg/L, kg/MJ, kg/kWh). For electricity and hydrogen, EF_i is the upstream WTT emission factors for power and hydrogen generation and distribution. For electricity distribution, an 8 percent transmission and distribution loss and charging efficiency loss is assumed.

- For exhaust air pollutants, CH_4, and N_2O:

$$E=\sum_i^N P_i \times EF_i \times VKT_i \qquad \text{(Equation 2)}$$

where,
E represents exhaust air pollutant, CH_4, or N_2O emissions (kg)
EF_i represents the emission factors for air pollutants, CH_4, and N_2O for vehicle segment i (kg/km)

- For evaporative air pollutants:

$$E=(EF_{running} \times \frac{VKT}{V} + EF_{soak+diurnal} \times 365) \times P_i \qquad \text{(Equation 3)}$$

where,
E is evaporative pollutant emissions (kg)
$EF_{running}$ is the emission factor for running losses (kg/hour)
$EF_{soak+diurnal}$ is the emission factor for hot soak and diurnal emissions (kg/day)
V is the average vehicle speed (km/hour)

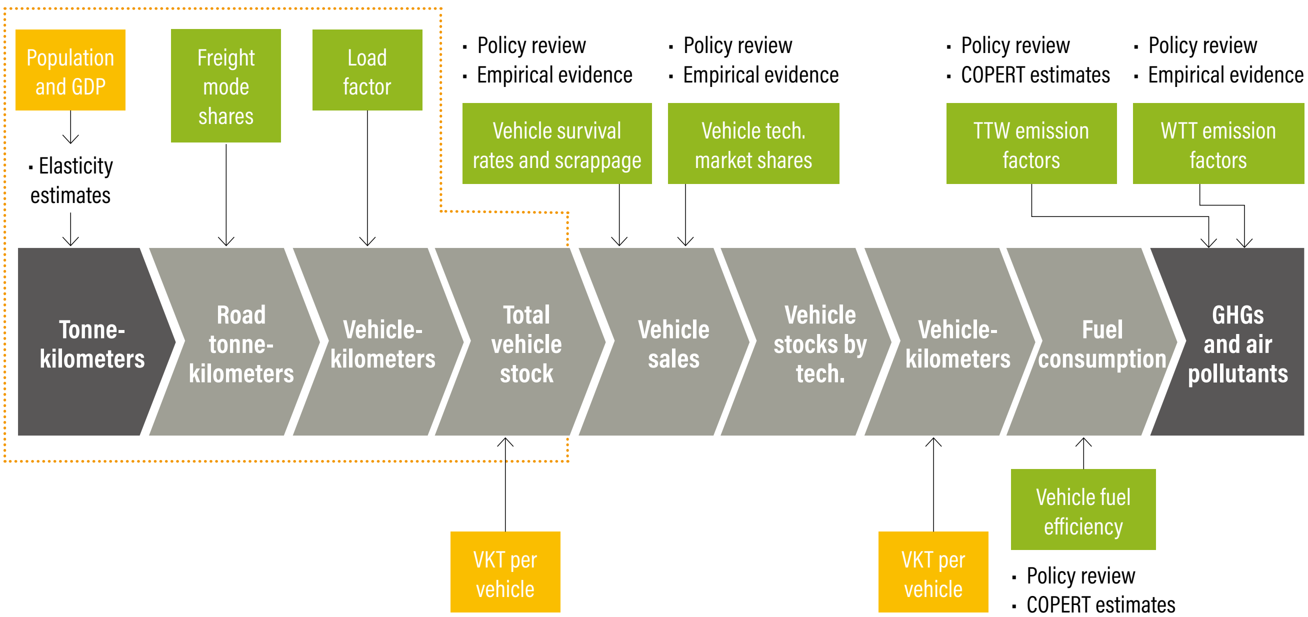
To forecast future emissions, we employed the vehicle fleet turnover model in LEAP. For each year, we projected the total number of vehicle stocks. Then we calculated annual vehicle sales based on vehicles' survival rates and the annual growth (or decrease) in vehicle stocks. We applied the market shares of different vehicle technologies to the new sales to obtain the fleet composition by vehicle technology. We used the latter for emission forecasting following Equations 1, 2, and 3.

As a technology-rich model, LEAP is capable of modelling the decarbonization potentials of low-carbon technology deployment. However, it does not model the effects of structural changes (including mode shift and vehicle occupancy improvements) well. To make up for this weakness, we developed a Microsoft Excel–based model to forecast future travel demand and vehicle stocks affected by structural changes. Because of varying degrees of data availability, we used a tonne-kilometer (tkm) method for freight transport and a vehicle-centric method for passenger transport (see Figures 3 and 4 and Appendix A).

Using the tkm method, we projected future freight vehicle stocks based on the growth in domestic freight tkm, mode share of road freight, and truck load improvements. Therefore, the effects of structural changes were explicitly modelled for freight transport. However, applying the same method to passenger transport was challenging because data on the total passenger kilometers travelled (pkm) and vehicle occupancy rates were not available—China's official statistical system does not cover the travel activities of private cars. Therefore, we used the vehicle-centric method for passenger transport, where passenger vehicle stocks were projected based on historical trends and qualitative evaluations of the impacts of structural changes based on a literature review.

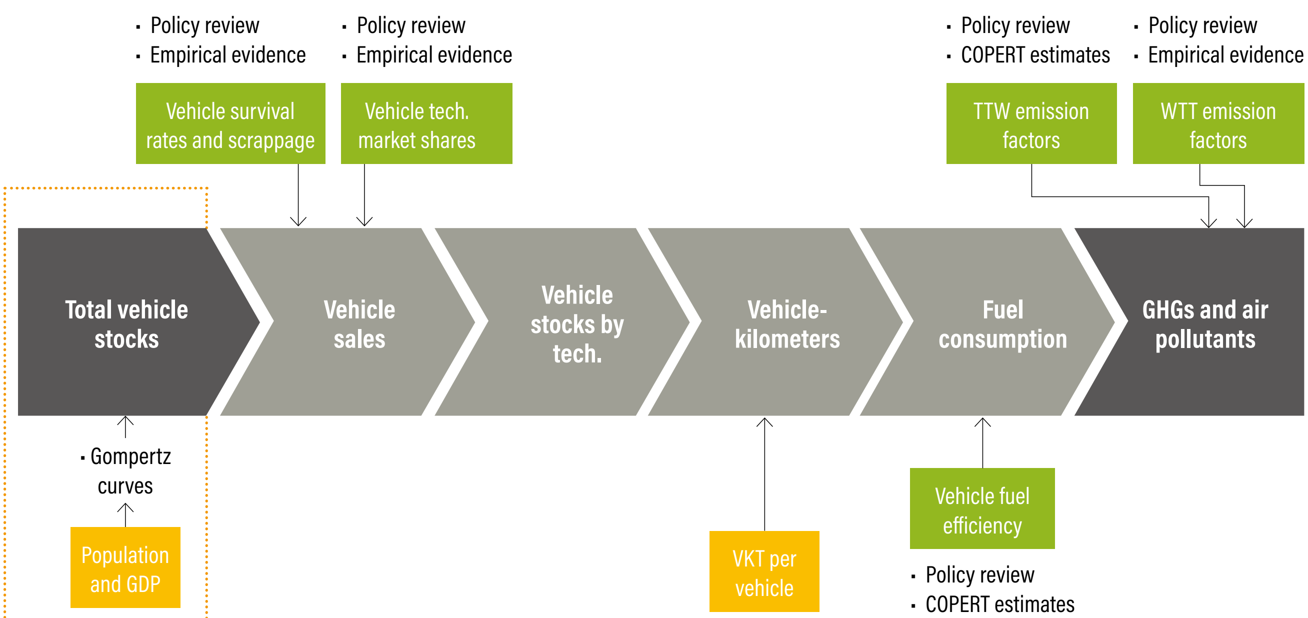
We localized the model inputs based on official statistical data, model estimates, a literature review, and expert consultations. See Table 3 for a qualitative assessment of the quality of the data inputs. As the emission estimates from bottom-up approaches are affected by the limited data quality of vehicle kilometers travelled (VKTs), we validated the bottom-up emission estimate in the base year with the top-down estimate using national energy balances.

Figure 3 | Emission Forecasting for Freight Transport



Notes: The dotted box areas represent the calculations performed in the authors' Microsoft Excel-based model. The unshaded areas represent the work performed in the Low Emissions Analysis Platform model.
Abbreviations: GDP = gross domestic product; tech. = technology; VKT = vehicle kilometers travelled; GHG = greenhouse gas; TTW = tank to wheel; WTT = well to tank; COPERT = A software program used to calculate air pollutant and GHG emission factors for the road transport sector (Ntziachristos et al. 2009).
Source: WRI authors.

Figure 4 | Emission Forecasting for Passenger Transport



Notes: The dotted box areas represent calculations performed in the authors' Microsoft Excel-based model. The unshaded areas represent the work performed in the Low Emissions Analysis Platform model.
Abbreviations: GDP = gross domestic product; tech. = technology; VKT = vehicle kilometers travelled; GHG = greenhouse gas; TTW = tank to wheel; WTT = well to tank; COPERT = A software program used to calculate air pollutant and GHG emission factors for the road transport sector (Ntziachristos et al. 2009).
Source: WRI authors.

Table 3 | **Qualitative Assessment of the Data Sources Used to Estimate Emissions**

VARIABLES	SOURCES	DATA QUALITY
Vehicle stocks in base year	NBS 2021	*High* [a]
Vehicle age profiles in base year	NBS 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021 CAAM 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020	*High*
Vehicle survival rates	ANL 2018	Medium Zero-emission vehicles' survival rates are assumed to be the same as those for ICE vehicles.
Freight tonne-kilometers in base year	NBS 2021	*High*
Penetration of different technologies in vehicle stocks	NBS 2021 Expert consultations	*High*
Vehicle kilometers travelled (VKTs)	MEE 2014b RIOH and Sinoiov 2021 WRI authors' adjustments (Annual VKTs are fixed throughout a vehicle's lifetime; degradation in VKTs as the vehicle ages is not considered. Further, the VKTs of NEVs are assumed to be the same as the VKTs of ICE vehicles.)	*Low* VKTs are sample-dependent, and the variation is large across sources.[b]
Fleet-average fuel efficiency in base year	This study's estimation using the COPERT model (Ntziachristos et al. 2009), using China-specific driving cycles such as the China Light-Duty Vehicle Test Cycle (CLTC) and China Heavy-Duty Commercial Vehicle Test Cycle, and assuming four-month A/C usage, and 50% vehicle load.	*Medium* Real-world fuel consumption is affected by a basket of factors such as travel speeds, slopes, A/C usage, and loads that would be challenging to capture in a single value. Further, the fleet mix also affects fleet-average fuel efficiency.
Load factors in base year	This study's calculations are based on the statistics for freight tonne-kilometers, vehicle stocks, and VKTs.	*Low* The limited quality of VKT data has ripple effects on load factors.
Market shares of NEVs in annual sales by vehicle segment	The base year's market shares are from the China Automotive Technology and Research Center in-house database. For projections, values are based on the authors' literature and policy document reviews.	*High*
Air pollutant, CH_4, and N_2O emission factors	Air pollutant emission factors come from the following sources: · MEE 2014b. · This study's estimation using the COPERT model (Ntziachristos et al. 2009), for the emission factors of hybrid vehicles and the vehicles in compliance with the China 6 emission standard. · NG vehicles' TTW CH_4 emission factors are based on Pan et al. (2020). (Emission factors are fixed throughout a vehicle's lifetime; degradation of aftertreatment systems as the vehicle ages is not considered.)	*Medium* Like fuel consumption, air pollutant emissions factors are affected by multiple factors such as weather, fuel quality, loads, and degradation of aftertreatment devices, which would be challenging to capture in a single value.
Power generation emission factor in base year	CEC 2020	*High*
Hydrogen generation emission factor in base year	This study's estimation using the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET 2.0) Model (ANL 2014), based on the current hydrogen generation mix (CSI 2018).	*High*

Notes: a. ● represents a high level of confidence, ◕ represents moderate confidence, and ◔ represents a low level of confidence. b. Song 2017.
Abbreviations: VKTs = vehicle kilometers travelled; ICE = internal combustion engine; A/C = air conditioning; NEV = new energy vehicle; CH_4 = methane; N_2O = nitrous oxide; TTW = tank to wheel.

2.2.2 Abatement cost calculation

We estimated the marginal abatement cost—the abatement cost per unit of emissions reduced in a given year (Equation 4)— for different mitigation policies and technologies to evaluate their cost-effectiveness.

$$\textit{Marginal abatement cost} = \frac{\textit{Abatement cost}}{\textit{Emissions abated}} \qquad \text{(Equation 4)}$$

As depicted in Equation 5, abatement costs are the net present values of the costs (such as expenses related to infrastructure investments) and savings (such as fuel cost savings) associated with the mitigation measures. These costs or savings could be assessed from the perspective of the end users or that of the society. When taking the societal perspective, taxes and subsidies are excluded as they are transfers between entities within a society, while taxes and subsidies are included when calculating from the end-user perspective (Schroten et al. 2012). This study took a societal perspective and excluded tax rebates and subsidies from the analysis. Therefore, the following costs are societal costs, including both public and private investments.

$$\textit{Abatement cost} = \frac{\textit{Total cost-total savings}}{(1+\textit{discount rate})^{\textit{year t}}} \qquad \text{(Equation 5)}$$

The estimation of abatement costs is distinguished by the mitigation measures:

- The abatement cost of alternative vehicle technologies: Taking electric vehicles (EVs) as an example, the abatement cost is the difference between the total cost of EV ownership and the total cost of internal combustion engine (ICE) vehicle ownership (Equation 6). The total cost of EV ownership in a given year is the EV's lifetime total cost of ownership (TCO)[iv] multiplied by the annual sale volume of EVs. The lifetime TCO of EVs consists of upfront vehicle purchase costs, energy costs, and levelized costs of charging/refueling throughout the vehicle's useful life. The levelized costs of charging/refueling denote the total capital expenses (CAPEX) and operating expenses (OPEX) of charging/refueling infrastructure[v] amortized to the EV's total energy demand. As explained earlier, we excluded taxes and subsidies from the study.

$$\textit{Abatement cost} = \frac{(EV_{capital,t}+EV_{operation,t})\times Sales_t - ICE_{cost_t}\times Sales_t}{(1+r)^{\textit{year t}}} \qquad \text{(Equation 6)}$$

where,

$EV_{capital,t}$ is the EV's purchase cost without taxes and subsidies in year *t*

$EV_{operation_t}$ includes lifetime electricity or hydrogen costs of the EV purchased in year *t*

ICE_{cost_t} is the lifetime TCO of a new ICE vehicle in year *t*

$Sales_t$ is the sales volume of EVs in year *t*

r is the annual social discount rate (3 percent in this study)

- The abatement cost of structural changes includes CAPEX and OPEX investments in transit, active mobility, and railway infrastructure as well as the cost savings from owning a smaller vehicle fleet under the effect of structural changes. Specifically, in a given year, structural change measures quantified by infrastructure investments lead to fewer vehicle sales ($Sales_t$) than the vehicle sales in the baseline scenario ($Sales_{t,no\_shift}$) without the effect of structural change measures (that is, no infrastructure investment). The difference in the total cost of vehicle ownership resulting from different sales volumes is attributed to the deployment of structural change measures. In this study, we did the calculation for passenger transport (Equation 7-1) and freight transport (Equation 7-2).

$$Abatement\ cost_{passenger} = \frac{Cost_{transit\_infrastructure,t}+(Cost_{capital,t}+Cost_{operation,t})\times Sales_t-(Cost_{capital,t}+Cost_{operation,t})\times Sales_{t,no\_shift)}}{(1+r)^{year\ t}} \quad \text{(Equation 7-1)}$$

where,
$Cost_{infrastructure,t}$ is the investment in transit and active mobility infrastructure in year t
$Sales_t$ is the sales volume of private cars by technology in year t with the effects of structural changes
$Sales_{t,no\_shift}$ is the sales volume of private cars by technology in year t without the influence of structural change measures
r is the annual social discount rate (3 percent in this study)

$$Abatement\ cost_{freight} = \frac{Cost_{railway\_infrastructure,t}+(Cost_{capital,t}+Cost_{operation,t})\times Sales_t-(Cost_{capital,t}+Cost_{operation,t})\times Sales_{t,no\_shift}}{(1+r)^{year\ t}} \quad \text{(Equation 7-2)}$$

where,
$Cost_{infrastructure,t}$ is the investment in railway infrastructure in year t
$Sales_t$ is the sales volume of trucks by technology in year t with the effects of structural changes
$Sales_{t,no\_shift}$ is the sales volume of trucks by technology in year t without the influence of structural changes
r is the annual social discount rate (3 percent in this study)

The cost inputs are based on official statistical data, a literature review, and expert consultations. See Table 4 for a qualitative assessment of the data sources used to evaluate abatement costs.

Table 4 | **Qualitative Assessment of the Data Sources Used to Estimate Abatement Costs**

VARIABLES	DATA AND SOURCES	DATA QUALITY
Vehicle purchase cost	Vehicle prices are from car dealer websites Diandong.com, Yiche.net, and 360che.com. Methods to project future vehicle costs are elaborated in Appendix B.	*High* [a]
Energy prices	Diesel: 6.5 CNY/L[b] Gasoline: 7.1 CNY/L[c] NG: 4.5 CNY/m^3 (2020) to 6 CNY/m^3 (2060)[d] Electricity: 0.6 CNY/kWh[e] (Energy prices are fixed despite market fluctuations and regional disparities.)	*Medium*
Levelized cost of charging stations' capital and O&M investments	0.5 CNY/kWh[f] (Levelized costs are fixed despite varying levels of investment)	*Medium*
Levelized cost of hydrogen[g]	2025: 40 CNY/kg (90–95% gray hydrogen in the production mix)[h] 2035: 30 CNY/kg (65–70% gray hydrogen in the production mix) 2050: 20 CNY/kg (15–35% gray hydrogen in the production mix)[i]	*Medium*
CAPEX and OPEX on freight railways	Assume that China's future freight infrastructure investments are linearly related to freight tkm growth and that a quarter of the freight investment goes to railways.[j]	*Low* The magnitude of investment varies by the actual demand for infrastructure.
CAPEX and OPEX on public transit and active mobility	Based on historical trends,[k] we assume that 700 km of subway is constructed each year until 2035.[l] The CAPEX of subways is fixed at 0.7 billion CNY/km. Due to their trivial amounts, we omitted investments in active mobility in this study.	*Low* The magnitude of investment varies by the type of infrastructure under discussion and the actual demand for infrastructure.

Notes: a. ● represents a high level of confidence, ◕ represents moderate confidence, and ◔ represents a low level of confidence.
b. Diesel prices are based on rough historical price trends from the past decade using CEIC Data (www.ceicdata.com).
c. Gasoline prices are based on rough historical price trends from the past decade using CEIC Data (www.ceicdata.com).
d. The current natural gas price is based on information from www.in-en.com. Future natural gas prices are projected based on WRI authors' assumptions.
e. Xue et al. 2020.
f. China EV 100 and NRDC 2019.
g. For fuel cell vehicles, this study assumes hydrogen production, transportation, distribution, capital expenses, and operating expenses of hydrogen refueling stations are altogether recouped by at-pump hydrogen costs, known as the levelized cost of refueling.
h. The hydrogen production mix is based on the authors' assumptions for different scenarios based on CHA (2019).
i. CHA 2019.
j. OECD 2018.
k. CAM 2017, 2018, 2019, 2020.
l. The assumed annual increase of 700 km of subway is consistent with the national target of increasing the subway length by 3,400 km over the 14th five-year period (2021–25).

Abbreviations: CNY = Chinese yuan; L = liter; m^3 = cubic meter; CAPEX = capital expenses; OPEX = operating expenses; kWh = kilowatt-hour; kg = kilogram; O&M = operations and maintenance.


38 出口
雍和宫桥
YONGHEGONG Bridge
1.6km
1 出口
小街桥
XIAOJIE Bridge
800m
2 出口
机场高速
三环路(三元桥)
200m

CHAPTER 3

SCENARIO DESIGN

Future emissions from the road transport sector are affected by factors such as service demand growth, structural changes, technology deployment, and upstream power and hydrogen sector decarbonization. The scenarios modelled in this study are based on existing policies and a literature review.

3.1 Influencing Factors

In general, future emissions from the road transport sector are affected by factors such as service demand growth, structural changes, technology deployment, and upstream power (and hydrogen) sector decarbonization (see Table 5). However, not all decarbonization measures are applicable to China (such as low-carbon fuels) or can be modelled by this study (such as carbon pricing). This section explains how we considered different measures. Further, because uncertainties remain large with autonomous driving, we did not cover that technology in this study.

3.2 Decarbonization Measures

The scenarios modelled in this study are based on existing policies and a literature review.

3.2.1 Service demand

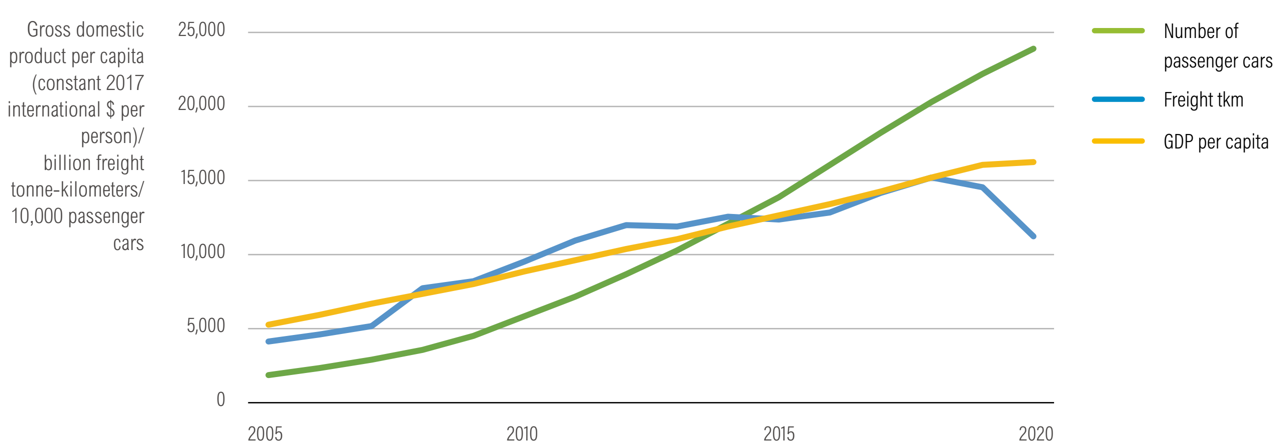
In contrast to the modest expected increases in travel demand in OECD countries over the next 30 years (Teske et al. 2021), China is expected to have strong growth in service demand during this period. In fact, the country experienced drastic growth in passenger and freight demand from 2005 to 2020 (Figure 5):

Table 5 | **Comprehensive Decarbonization Measures to Mitigate Road Transport Emissions**

	SERVICE DEMAND	STRUCTURAL CHANGES	TECHNOLOGY DEPLOYMENT	POWER AND HYDROGEN DECARBONIZATION
Decarbonization measures	▪ Compact development and land-use planning ▪ Fuel pricing and/or carbon pricing	▪ Mode shift ▪ Vehicle occupancy improvements	▪ Vehicle electrification ▪ Fuel efficiency improvements ▪ Low-carbon fuels	▪ Power sector decarbonization ▪ Hydrogen production decarbonization
Variables	▪ Vehicle stocks ▪ Domestic tkm ▪ Vehicle kilometers travelled	▪ Mode shares ▪ Load factors (tkm/vkm)	▪ Market shares of vehicle technologies ▪ Percent of fuel blends and carbon intensity in fuels ▪ Fuel efficiency	▪ Power mix ▪ Hydrogen production mix

Abbreviations: tkm = tonne-kilometer; vkm = vehicle-kilometer.
Source: WRI authors.

Figure 5 | **Growth in Passenger Car Ownership, Freight Tonne-Kilometers, and Gross Domestic Product per Capita (2005–20)**



Note: The decreases in the freight tonne-kilometers (tkm) during 2018 and 2020 were due to an adjustment in China's statistical system to exclude light-duty trucks' tkm; and the impacts of COVID-19 on waterway tkm.
Source: NBS 2021.

- The number of passenger cars in China increased 12 times from 19 to 239 million (compound annual growth rate, or CAGR, of 18 percent) (NBS 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020).

- Significant increases also occurred for China's domestic freight demand. The tonne-kilometers (tkm) (including domestic road, railway, waterway, aviation, and pipeline, but excluding international maritime shipping and aviation) were 15.2 trillion tkm in 2018, increasing more than three times (CAGR = 10.5 percent).

Future growth in passenger cars

Despite tremendous growth, the passenger car ownership rate in China—170 cars per 1,000 persons in 2020—is relatively low compared with Japan's 493, the EU's 540, and the United States' 592 (NBS 2020; MLITT 2021; Eurostat 2021a; BTS 2021a).

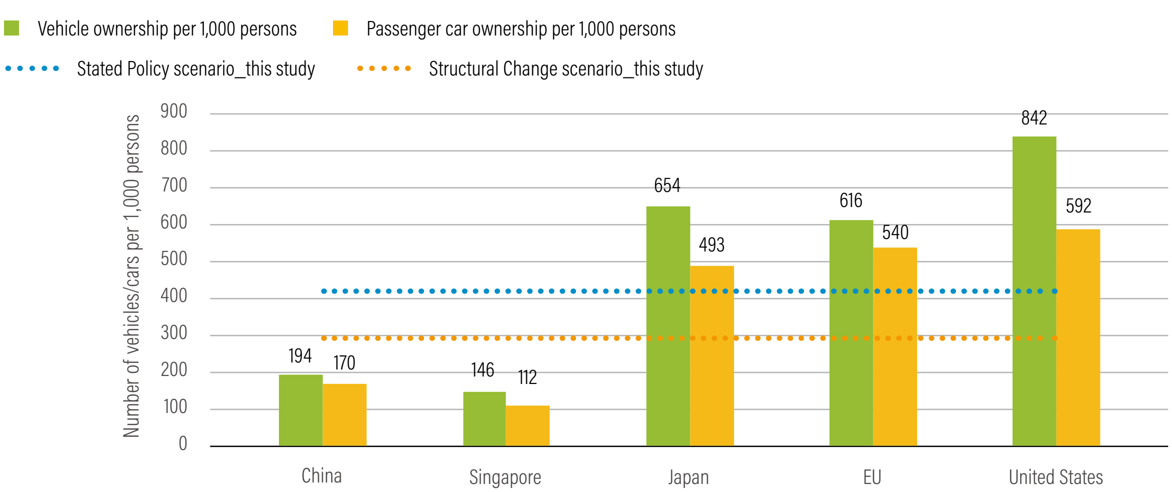
To project China's passenger car ownership up to 2060, we employed the Gompertz model, where the growth in car stocks follows an S-shaped curve—the growth in car ownership is rapid as gross domestic product (GDP) per capita increases but slows when approaching the saturation level. Our GDP and population forecasts are based on the Shared Socioeconomic Pathways (Riahi et al. 2012; see Appendix A). We cross-validated the result with existing studies.

The forecasts show that China's motorization will continue until a maximum saturation level is reached, though the saturation level for China's passenger cars will be lower than those in developed countries (Figures 6 and 7):

- Existing studies show that if no additional policy interventions are pursued, China's passenger car saturation will be likely around 350–450 passenger cars per 1,000 persons by 2050 (Gilbert 2017; ANL 2018; Huo et al. 2012a), amounting to 450–600 million car stocks. In the Stated Policy scenario of this study, the saturation level of passenger cars is set to 425 cars per 1,000 persons, with total passenger car ownership peaking in 2045 at 506 million vehicles.

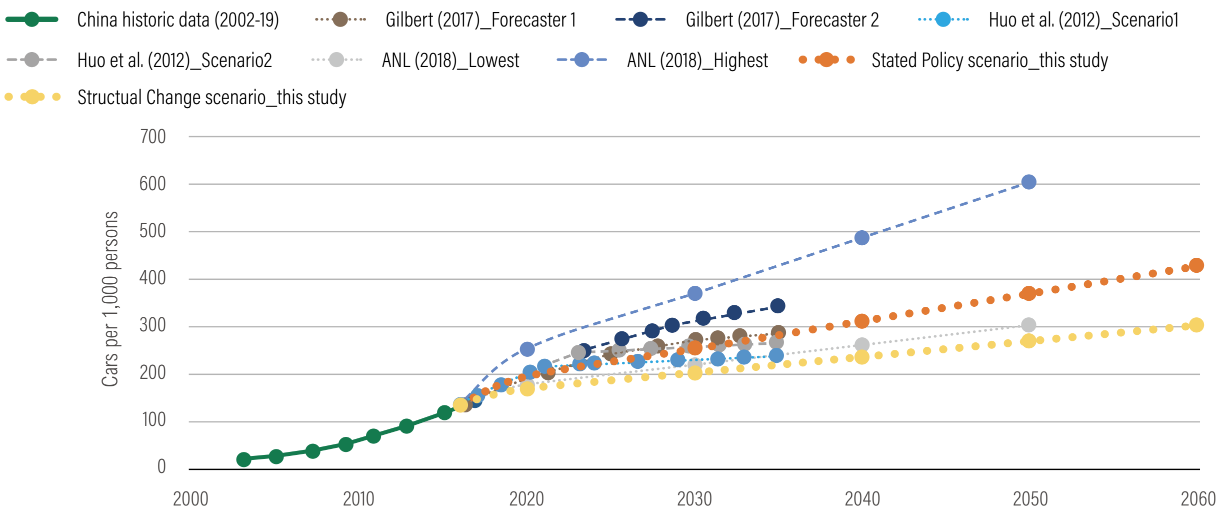
- Existing studies also reveal that if mode shift measures and compact urban planning are undertaken, the saturation level can be lowered to 260–350 passenger cars per 1,000 persons by 2050, amounting to 330–450 million car stocks (Gilbert 2017; ANL 2018; Huo et al. 2012a). In the Structural Change scenario of this study, the saturation level is lowered to 300 cars per 1,000 persons, with car ownership peaking in 2040 at 381 million vehicles.

Figure 6 | **Vehicle and Passenger Car Ownership per 1,000 Persons in China and Other Regions**



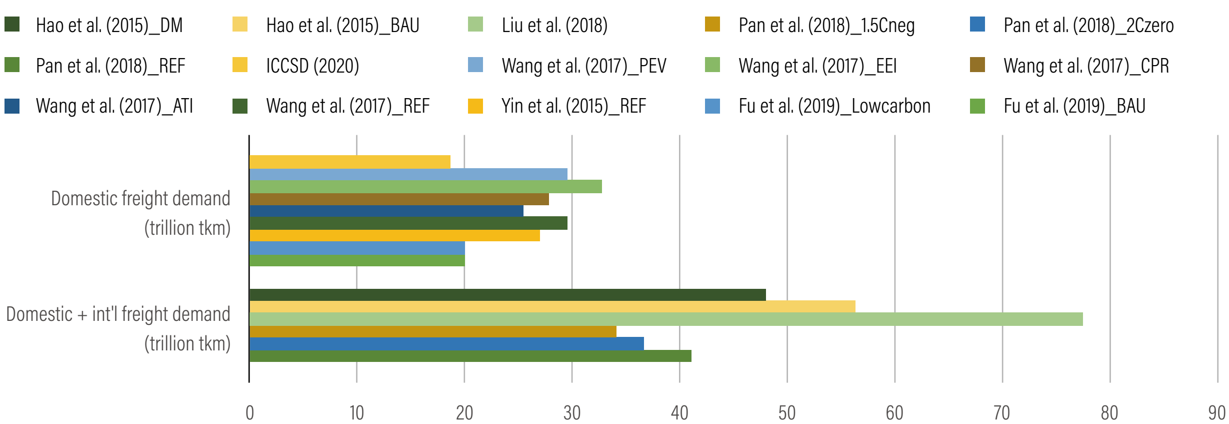
Note: European Union (EU) and United States vehicle and passenger car ownership data are from 2019; data for other countries are from 2020.
Sources: NBS 2021; LTA 2021; BTS 2021a; Eurostat 2021a; MLITT 2021. Population data come from the World Bank database: https://data.worldbank.org.

Figure 7 | **Predictions for Car Saturation Levels by Existing Research and This Study**



Sources: NBS 2019; Gilbert 2017; ANL 2018; Huo et al. 2012b; and author assumptions.

Figure 8 | **Existing Projections for China's Domestic Freight Tonne-Kilometers**



Note: Domestic freight demand includes domestic roads, railways, waterways, aviation, and pipelines, but excludes international shipping (maritime), aviation, and railways.
Abbreviations: tkm = tonne-kilometer; int'l = international.
Sources: J.L. Liu et al. 2018; ICCSD 2020; Pan et al. 2018; Wang et al. 2017; Yin et al. 2015; Hao et al. 2015; Fu et al. 2019; WRI authors.

Future growth in freight demand (in tkm)

Driven by economic growth, China's freight demand should continue growing; however, the growth rate is confounded by many uncertainties, including supply chain relocation, an economic structural shift to the less transport-intensive service sector (H. Wang et al. 2021),[vi] and long-term oil price changes. Therefore, views are divided on whether China's freight demand growth will be maintained (Figure 8).

- Some modelling studies (Fu et al. 2019; ICCSD 2020) have concluded that with the economic shift to less transport-intensive sectors and the expected decline in bulk commodity shipments (such as of coal and mineral ore), China's freight demand growth will slow starting in 2030 (CAGR = 0.6 percent) and plateau during 2040–45 at around 18.6–19.8 trillion tkm. Peak demand would be only 1.7–1.8 times the demand in 2020.

- Other research indicates that freight demand is affected by both transported tonnes and travel distances. Though transported tonnes—like bulk commodities—could drop, the distances travelled will likely grow given more frequent shipments and increases in shipment lengths, as in the case of Germany (Frey et al. 2014).

Therefore, to be comparable with the growth trends in developed countries,[vii] China's domestic freight demand in 2050 would be two to three times (25.2–32.5 trillion tkm) the level in 2020 (Yin et al. 2015; Wang et al. 2017).

This study takes an optimistic view on China's future freight demand given the promising demand forecasts in other regions. For example, according to Freight Analysis Framework, U.S. domestic freight demand will grow to 7.6 trillion ton-miles in 2045, only 1.5 times the tkm in 2015 (BTS and FHWA 2016). Germany's freight demand is projected to reach 896 billion tkm in 2050, 1.4 times the tkm in 2016 (Agora Energiewende 2020a). Using GDP per capita and fuel price elasticities—measurements of how freight demand responds to the growth of GDP per capita and fuel price increases (see Appendix A; Edelenbosch et al. 2017)—we project that China's domestic freight demand will reach 25.9 trillion tkm in 2060, 2.5 times the 2020 level.

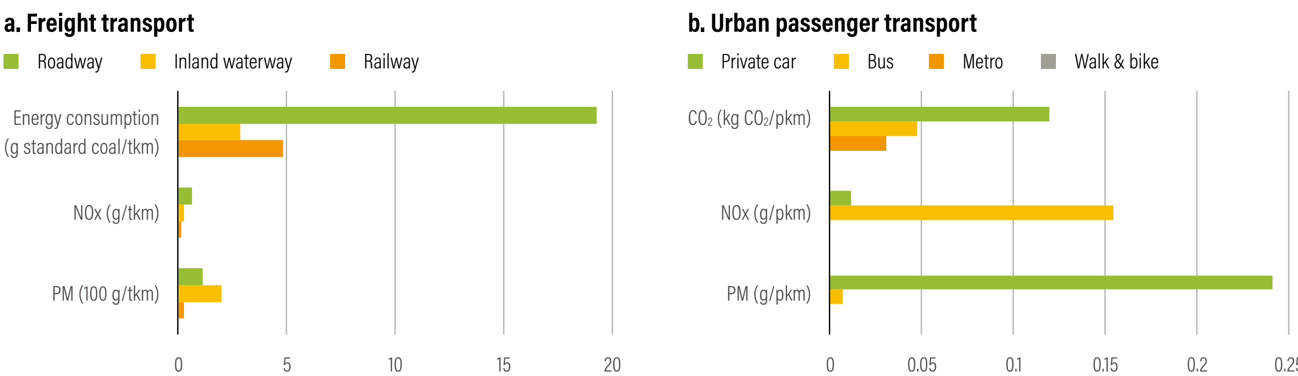
3.2.2 Structural changes

Because of high occupancy rates and low emission intensity per tkm or pkm, passenger and freight mode shifts are essential to reducing carbon footprints and alleviating traffic congestion (see Figure 9).

However, shifts to high-emitting modes are occurring in China (Figure 10):

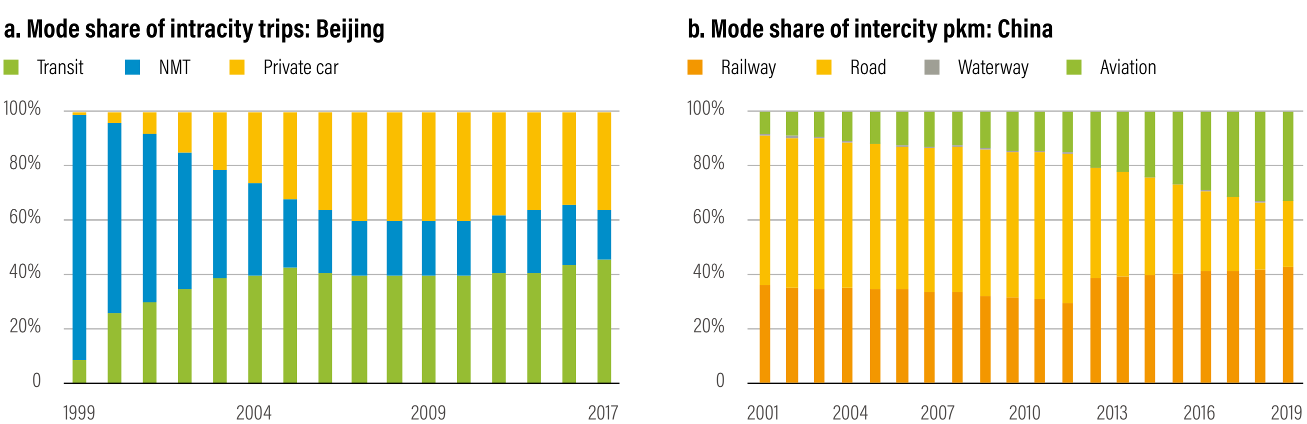
- Passenger transport: Due to rapid urban expansion, large cities have witnessed increases

Figure 9 | **Energy/Emission Intensities of Different Modes**



Abbreviations: CO_2 = carbon dioxide; kg = kilogram; g = gram; tkm = tonne-kilometer; pkm = passenger kilometers travelled; NOx = nitrogen oxides; g = gram; PM = particulate matter.
Sources: Energy consumption data for freight modes are from MOT (2016). Air pollutants from freight modes are calculated by the authors using MEE (2020b). Passenger modes are calculated by the authors using Shenzhen's vehicle occupancy rates. The CO_2 emission factor for metro is based on Jiang et al. (2019).

Figure 10 | **Changes in Passenger Transport Mode Share in China**



Notes: Walking is not included in Beijing's mode share.
Abbreviations: pkm = passenger kilometers travelled; NMT = non-motorized transit.
Source: Fu et al. 2019; NBS 2021.

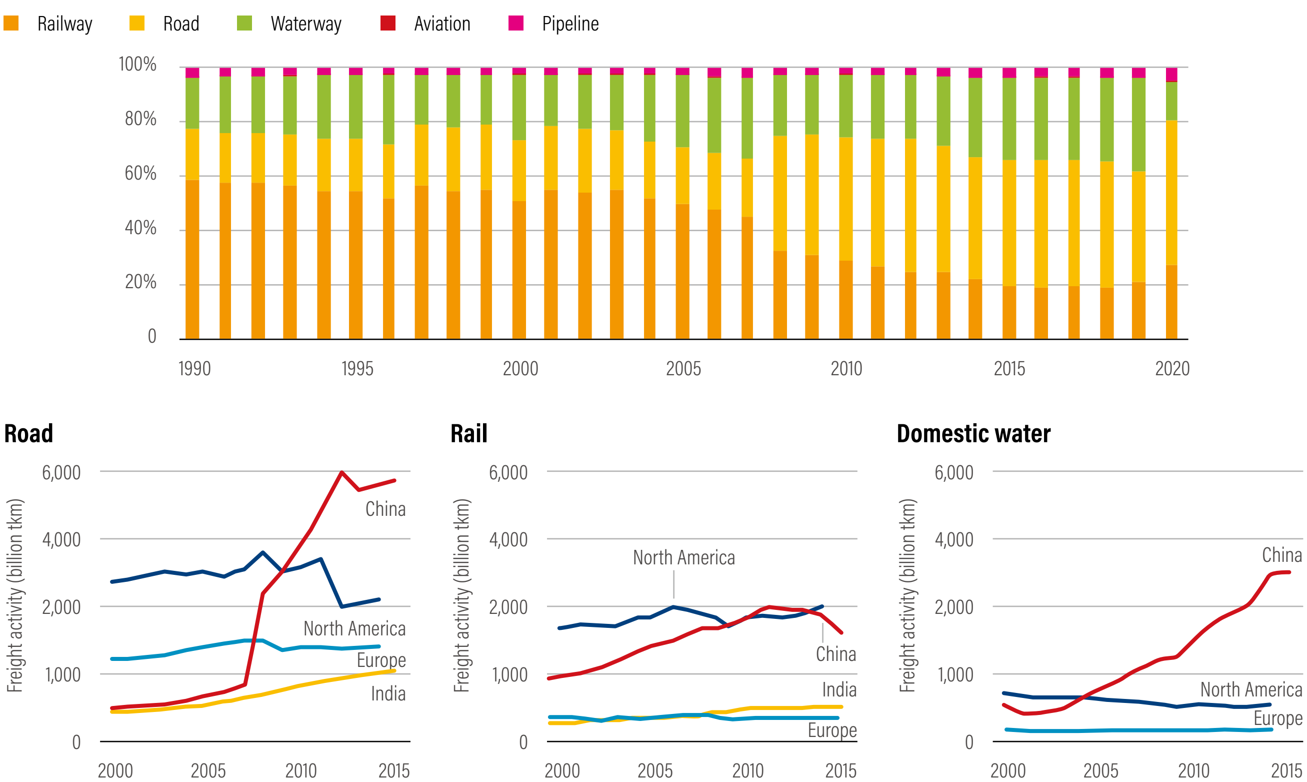
in motorized trips (private car and transit), leading to reduced non-motorized trips (such as biking and e-scootering). For example, the mode share by bike, e-scooter, and motorcycle in Beijing dropped from 90 percent in 1999 to 18 percent in 2017 (Fu et al. 2019), while the mode share of private cars (including ride-hailing) increased from 1 percent in 1999 to 36 percent in 2017.

The situation is mixed for intercity travel. From 2001 to 2020, the share of intercity pkm by car decreased from 55 to 24 percent, while the share of railways grew slightly from 36 to 43 percent. However, of note is that an increasing number of intercity travel is being undertaken by air, with aviation's mode share rising four times from 8 to 33 percent.

- Freight transport: Due to underpriced roadway freight,[viii] limited track access, and undesirable railway service quality from 1990 to 2020 (Agenbroad et al. 2016), the share of railways in domestic tonne-kilometers in China shrank drastically over that period from 59 to 27 percent (although the rail tkm increased almost threefold), while the share of road freight increased from 19 to 54 percent due to strong economic growth (Figure 11). During the same period, domestic waterways experienced a slight drop from 19 to 14 percent.

Compared with North America, Europe, and India, China is more reliant on roadways and waterways for freight shipments, with roadway and waterway tkm increasing by seventeen-fold and thirteen-fold, respectively, from 1990 to 2019. Nonetheless, compared with the United States' recent increase in domestic railway activities—resulting from the transition from railway-based coal shipments to intermodal freight, China's rail activities have not grown since 2010 (Kaak et al. 2018).

Figure 11 | **Freight Mode Share of Domestic Tonne-Kilometers in China and Comparisons with North America, Europe, and India**



Notes: Domestic freight mode share includes roads, railways, waterways, aviation, and pipelines, but excludes maritime. Abbreviation: tkm = tonne-kilometer.
Sources: NBS 2021; Kaak et al. 2018.

Passenger transport mode shift

Unlike countries like the United States where interventions like mode shift and increasing vehicle occupancy are less effective due to the lock-in effect resulting from an already-high dependency on private cars (Teske et al. 2021), high-density Chinese cities are likely to reverse the ongoing passenger mode shift to private cars. This is particularly the case considering many small cities in China still have a private car mode share of around 10–15 percent (ZTB 2017).

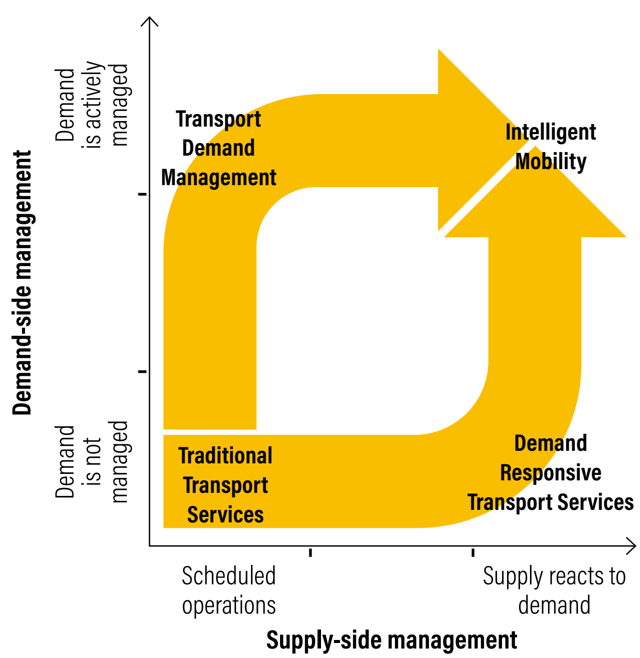
This study assumes that in the Stated Policy scenario—which is based on NDRC (2021)—that by 2030, major Chinese cities will have over 70 percent green transport mode share in which public transit accounts for 45 percent of the total mode share (ICCSD 2020). In the Structural Change scenario, to keep car ownership (and usage) at a reasonably low level, the green transport mode share should be elevated to about 75–85 percent, and public transit should represent over 50 percent of the total mode share (ICCSD 2020). These targets are achievable: By prioritizing cycling and walking and strengthening modal integration, Shenzhen's and Beijing city center's green transport mode shares reached 77 percent and 73 percent, respectively, in 2020 (*China Transport News* 2021; *Xinhua News* 2021).

To achieve the elevated targets in the Structural Change scenario, the country should embrace a paradigm shift from provider-oriented green transport services to user-oriented services (Figure 12; Enoch 2018). Although shared rides (such as ride-hailing and carsharing) are integral to this paradigm shift, additional measures should be taken to avoid their competition with public transit and increased "deadhead" miles (Kong et al. 2020; Schaller 2021; Zhang et al. 2020). These measures, including Mobility-as-a-Service (MaaS), should enable ride-sharing to supplement transit services in places of limited transit accessibility and allow for better journey matches to reduce deadhead miles (ERTICO 2019).

Freight transport mode shift

Although the movement up the value chain and new logistics requirements (increasing shipments of smaller parcels and just-in-time delivery) inherently favors roadways, China has an untapped potential to increase rail freight's mode share. Research shows countries with large land coverage and good railway networks such as Russia, Australia, and

Figure 12 | **Paradigm Shift in Transit Services: From Provider-Oriented Services to User-Oriented Services**



Source: Enoch 2018.

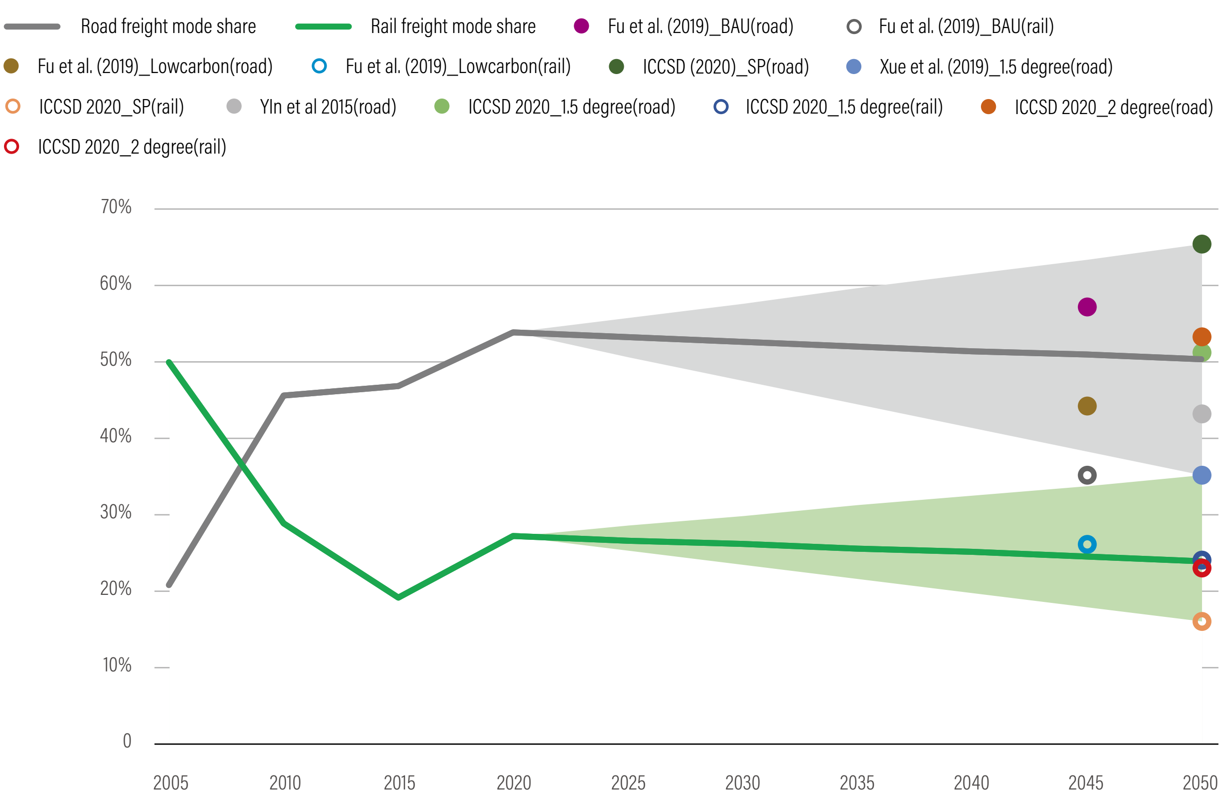
Canada tend to have higher rail shares than the world's average of road and rail mode split—61:39 (Kaak et al. 2018), with China as an exception. This is mainly due to uncompetitive railway pricing,[ix] underdeveloped intermodal services, and limited rail service quality in China (Agenbroad et al. 2016). For example, for shipment distances over 400 kilometers, bulk unit trains were about 2–20 CNY per tonne more expensive than roadways in 2018 (H.H. Liu 2018). Further, intermodal (containerized) rail services are underdeveloped in China: Only 5.4 percent of the rail shipments (by weight) were intermodal containers in 2016 (Fu et al. 2019), compared with 19 percent in European countries (Eurostat 2021b).

Because China lacks a national freight mode shift target and a statistical system to evaluate future mode shift potential, this study relies on existing research to project freight mode share. However, we recommend making substantial improvements to the country's freight statistical system to incorporate surveys on commodity flows (by mode, distance, and origin/destination pairs), which would allow for mode shift target setting and policymaking based on commodity-specific evaluations.

For simplicity, this study assumes under the Stated Policy scenario that a larger shift to road transport could be prevented (Table 6), whereby road transport would represent 50 percent of the domestic tkm in 2060 (about 2020's level). This is consistent with the median value of the existing predictions (J.L. Liu et al. 2021; ICCSD 2020; Pan et al. 2018; Wang et al. 2017; Zhang et al. 2016; Yin et al. 2015; Hao et al. 2015; Huo et al. 2012a) (Figure 13).

Under the Structural Change scenario, this study assumes that an explicit mode shift target—40 percent road transport in domestic tkm in 2060—will be established (Figure 13). To achieve this target,

Figure 13 | **Projections of China's Future Freight (Railway and Roadway) Mode Shares out of Total Domestic Tonne-Kilometers in Existing Studies**



Note: China's freight mode share includes roads, railways, waterways, aviation, and pipelines, but excludes maritime.
Sources: Historic mode share data for road freight and rail freight are from NBS (2021). Further projections are based on ICCSD (2020); Xue et al. (2019); Fu et al. (2019); Yin et al. (2015).

Table 6 | **Policies and Announced Targets in the Stated Policy Scenario**

RAILWAYS AND WATERWAYS

Invest in railways, waterways, and intermodal connectivity.[a]

- By 2025, the volume of containerized intermodal railway shipments will increase by 15%; 85% of major container ports must be equipped with on-dock rail services; and 85% of new logistic parks and large industrial enterprises must have rail track access.
- Accelerate the expansion of high-grade inland waterways.

Reduce shipping time.[b]

- By 2035, increase the mode share of intermodal freight, and reduce intermodal handling/transit time.
- Promote standardization of intermodal handling equipment and data exchanges.

ROADWAYS

Manage oversupply, underbidding, and thin margins in the truck industry.[c]

- Promote internet freight platforms for better load matching and more high-value services (such as supply chain and inventory management).
- Prohibit internet freight platforms from encouraging shippers to lower shipping prices and drivers to underbid.

Avoid vehicle overloading.[d]

- Tighten the scale of enforcement on truck overloading.
- Avoid illegal adaptations to vehicles or mislabeled gross vehicle weights.

Note: [a] NDRC 2021; State Council 2021a. [b] State Council 2021b. [c] MOT 2019. [d] MOT 2017a, 2017b.
Source: WRI authors, summarized based on policy documents.

systematic measures will need to be undertaken:

- For the rail sector: In the near term, the country could shift more bulk commodities to railways and waterways, considering roadways still dominate shipments of steel, cement, and gravel (Fu et al. 2019). Over the long term, as the country moves up the value chain, and the volumes of bulk commodity shipments drop, transitioning to intermodal freight for high-value products will be necessary. This transition would mean new geographical patterns of rail activities, new investment needs, and higher service requirements (SFC n.d.; Kaak et al. 2018) for railway companies. The railroad industry, which has been monopolized by state-owned enterprises, will need to enhance service connectivity among rail segments, rationalize pricing, improve scheduling and on-time performance, automate freight (un)loading, avoid loss/breakage, and reinforce first-/last-mile truck delivery.

- For the road sector: Interventions are needed to tackle China-specific challenges including truck capacity oversupply, underpriced road shipments, and thin profit margins that are crucial to improving the cost-competitiveness of rail services (for concrete interventions, see *Vehicle occupancy rate improvements).*

Vehicle occupancy rate improvements

Improving vehicle occupancy rates is critical to reducing vehicular emissions because the same demand can be fulfilled with fewer vehicles.

For passenger transport, although ride sharing is an important measure to increase the occupancy rate for private cars, priority should be given to increasing occupancy rates for public transit. This is particularly the case when many Chinese cities have witnessed declining bus ridership and low bus occupancy: For example, the average occupancy rate of buses was 22 percent in Shenzhen in recent years (in terms of the carrying capacity for a mainstreamed 10-meter bus), smaller than Hong Kong's roughly 30–85 percent (in terms of the carrying capacity for a mainstreamed three-axle double-decker) (Lai n.d.). To increase ridership, rationalization of traditional bus services, introduction of demand-responsive services, and comprehensive travel demand management measures are necessary.

For road freight transport, operational efficiency needs to be significantly improved. With tightened controls over truck overloading (MOT 2017a),[x] the average load of road freight (quantified by dividing annual tonne-kilometers

Table 7 | **Operational Efficiency of the Truck Industry in China, the European Union, and the United States**

	CHINA (2020)	EU 27 (2020)	UNITED STATES (2018)
Tonne-kilometers of road freight	6,017 billion[a]	1,803 billion[b]	2,969 billion[c]
Annual VKTs of heavy-duty trucks (kilometers)	46,808[d] or 65,171,[e] depending on source	74,000–114,000[f]	96,446 (combination trucks)[g]
Average load	9.5 tonnes[h]	11.5 tonnes[i]	--
Empty running	40%[j]	20% [k]	20%[l] (for hire)
Number of trucks	30.4 million[m]	31.5 million[n]	13.1 million[o]
Number of heavy-duty trucks	8.4 million[p]	1.7 million[q]	2.9 million[r] (combination trucks)

Note: Light-duty trucks' tonne-kilometers (tkm) are not included in China's statistics for road freight tkm. The number of trucks includes both light-duty trucks (for China, light-duty trucks are those with gross vehicle weights [GVWs] below 4.5 tonnes; for the European Union [EU], light-duty trucks are those with GVWs below 3.5 tonnes) and heavy-duty trucks. In China and the EU, heavy-duty trucks refer to trucks with GVWs over 12 tonnes; in the United States, heavy-duty trucks include only combination trucks (class 8 tractor trailers).
Abbreviations: EU 27 = the 27 members of the European Union.
Sources: a. NBS 2021. b. Eurostat 2021d. c. BTS 2021a. d. RIOH and Sinoiov 2021. e. CATARC 2018. f. Gnann et al. 2017. g. FHWA 2021. h. Authors' calculation based on the method outlined in Table 3. i. Eurostat 2021c. j. Yang et al. 2019. k. Yang et al. 2019. l. ATRI 2020. m. NBS 2021. n. Eurostat 2021e. o. BTS 2021a. p. NBS 2021. q. Eurostat 2021e. r. BTS 2021a.

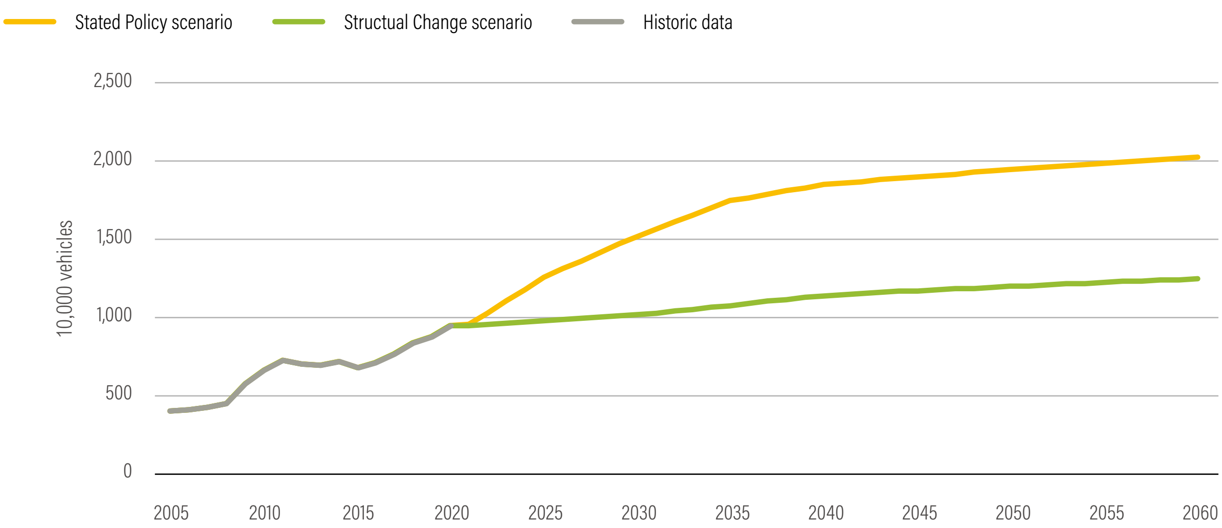
by total vehicle-kilometers) had declined to 9.8 tonnes in 2020, lower than the EU's 11.5 tonnes (Eurostat 2021c). Further, 40 percent of China's vehicle-kilometers were empty running, compared with the EU's and United States' 20 percent (Yang et al. 2019; ATRI 2020).

Due to operational inefficiency, the size of the heavy-duty truck fleet is excessively large in China: Though China's road freight tkm were two to three times higher than those in the EU 27 and the United States in 2020, the number of heavy-duty trucks in China was three to five times higher than those in the EU 27 and the United States in the same year (Table 7). If the issues with truck underutilization and oversupply persist, they will intensify the unhealthy competition (such as underbidding of roadway prices) within the trucking industry and deter freight mode shift to low-carbon modes.

Underutilized trucks, inefficient operations, and a dependency on road freight will further boost future truck fleet sizes. By this study's estimates, in the Stated Policy scenario where trucks remain inefficiently operated (with an average load of 9.5 tonnes) and roadways consist of 50 percent freight tkm, China's future fleet size of medium- and heavy-duty trucks (GVWs above 4.5 tonnes) will double from 9.5 million in 2020 to 20 million in 2060. However, in the Structural Change scenario, with operational efficiency improvements (average load = 11.5 tonnes) and freight mode shift, the future fleet size of HDTs will be maintained at 12 million in 2060, only a modest 26 percent increase from the 2020 level and half the fleet size in the Stated Policy scenario (Table 14).

Although there is an upper limit to logistic efficiency improvements—given a geographical imbalance in freight flows; growing lightweight and low-density freight (McKinnon 2010); and the increasing adoption of NEV trucks (Qiu et al. 2020), which will affect HDTs' operational efficiency—it is possible to achieve the level of operational efficiency in the Structural Change scenario. For example, Mulholland et al. (2018) show that average loads of HDTs increase with a country's average income due to the shift from straight trucks to tractor trailers and combination trucks for long-haul transportation. Additional

Figure 14 | **China's Heavy-Duty Truck Fleet Size Projections (2020–60) under Different Scenarios**



Sources: Historic data are based on NBS (2021). Projections are WRI authors' calculations.

measures China could use to improve road freight operational efficiency include encouraging the use of non-truck operating carriers, facilitating drop-and-hook operations, and promoting standardization of trucks and pallets (Agenbroad et al. 2016).

3.2.3 Technology deployment

Low-carbon vehicle technologies (or fuels)

The low-carbon transition in China's vehicle fleet is rapidly underway (Table 8 and Figure 15).

New energy vehicles (NEVs)—including battery electric vehicles, plug-in electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs)—are becoming mainstream technologies in buses and being increasingly adopted for use in private cars.

- NEV buses had a 55 percent fleet penetration by the end of 2020, rising rapidly from 2012's 3 percent. NEV taxis are also gaining market momentum, representing 9 percent of fleet penetration.

- Although NEV private cars had a 1 percent fleet penetration by the end of 2020, the market share of NEV sales soared: NEVs accounted for 15.7 percent of passenger car retail sales in 2021, more than double 2020's 6 percent (CAAM 2022).

- By contrast, the fleet penetrations and market shares of NEVs remain low for light-duty and heavy-duty trucks: NEVs account for 0–1 percent of heavy-duty truck and light-duty truck fleet penetration, and 1 percent market share in their respective annual sales.

NG vehicles are common for commercial fleets: They have 55 percent of the taxi fleet penetration and 18 percent of the bus fleet penetration. They are increasingly adopted by the trucking industry (5 percent of the heavy-duty fleet penetration in 2020), and the market share of liquefied natural gas (LNG) trucks in heavy-duty truck sales tripled from 2.4 percent in 2015 to 8.5 percent in 2020 (Autoinfo 2021).

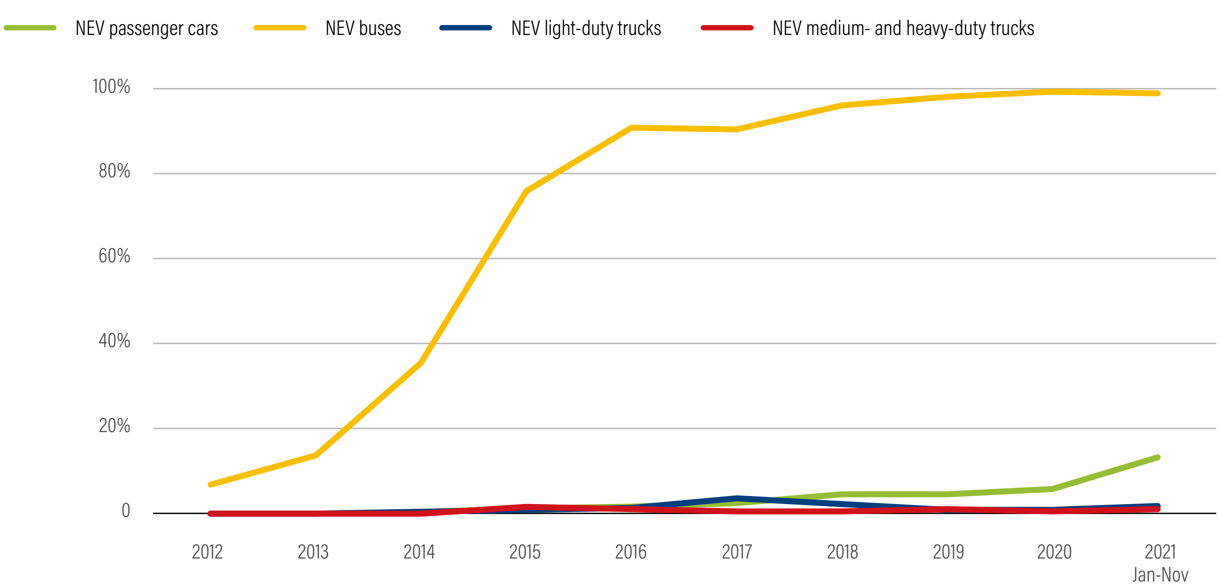
Not all alternative vehicles/fuels are popular, especially biofuels. Unlike in the United States where most of the gasoline sold is blended with 10–15 percent ethanol (by volume), biofuels are the least-adopted type of fuel in China. At present, biofuels—especially ethanol—are applied mostly to the taxi fleet, with 11 percent of the fleet powered by ethanol.

Table 8 | **Fleet Penetration of Alternative Vehicles/Fuels in 2020**

	SHARE OF THE TOTAL STOCK	GASOLINE	DIESEL	HYBRID	NATURAL GAS	NEV	OTHERS (ethanol, LPG)	SUBTOTAL
Private cars	70%	98%	0%	1%	0%	1%	0%	100%
Taxis	0%	22%	0%	1%	55%	9%	13%	100%
Buses	0%	0%	14%	12%	18%	55%	1%	100%
Coaches	1%	3%	87%	0%	6%	4%	0%	100%
Light-duty trucks	6%	42%	56%	0%	1%	1%	0%	100%
Heavy-duty trucks	3%	0%	95%	0%	5%	0%	0%	100%
Motorcycles	20%	100%	0%	0%	0%	0%	0%	100%

Note: Because of the data constraint regarding the technology breakdown for motorcycles, the study assumes 100 percent of the registered motorcycles are powered by fossil fuels, and unregistered motorcycles (and e-scooters) are electric.
Abbreviations: NEV = new energy vehicle; LPG = liquefied petroleum gas.
Sources: Data on private cars, coaches, light-duty trucks, and heavy-duty trucks are from a China Automotive Technology and Research Center (CATARC) database (accessed November 2021). Data on taxis and buses are from MOT (2020). The breakdown of motorcycle technology is based on WRI authors' assumptions.

Figure 15 | **Market Share of New Energy Vehicles in Annual Sales of Respective Vehicle Segments (2012–November 2021)**



Abbreviations: NEV = new energy vehicle.
Source: Data are from a China Automotive Technology and Research Center (CATARC) database (accessed November 2021).

First, the future technology pathways are country-specific and vehicle segment-specific. Particularly, controversies lie in the plausibility of using "transitional technologies." For example, some studies argue that despite their inferior environmental performance, the transitional technologies are necessary near-term options for China:

- LNG trucks: 50 percent fleet penetration in 2050 (LBNL 2021)
- Biofuels: 32 percent of transport energy consumption in 2050 (Pan et al. 2018)
- Hybrid trucks: 40 percent of annual sales by 2060 (iCET 2021)

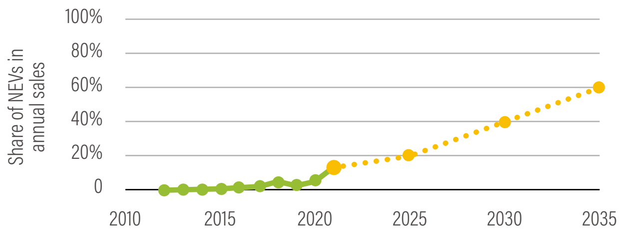
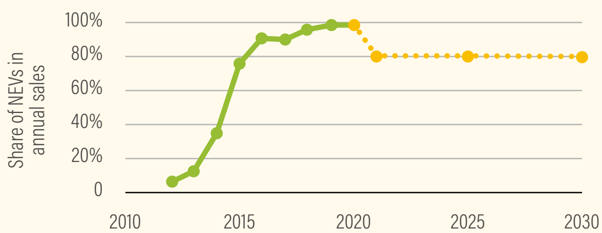
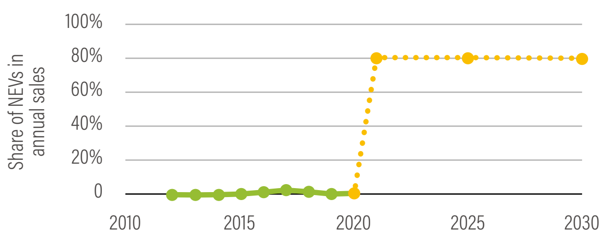
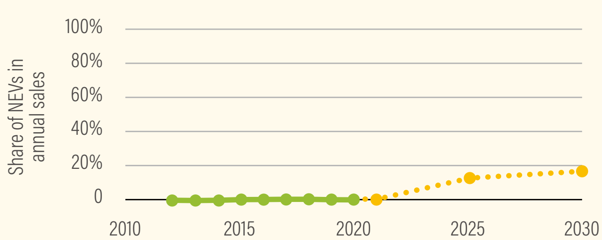
Considering the infrastructure investment needs and useful lives of vehicles, this study gave only limited consideration to transitional technologies:

- For passenger cars and light-duty trucks, we focused on battery electric vehicles (BEVs) because of the dominance of BEVs in market shares. For passenger cars, China's ratio of BEVs in passenger NEV sales has been around 80 percent since 2016, higher than the EU's 45–51 percent (ACEA 2021) and the United States' 54–78 percent (BTS 2021b). For trucks, BEVs are more predominant, accounting for 99.1 percent of NEV truck sales in 2020. Increasing numbers of regions such as the United Kingdom; California, United States; and Hong Kong have placed PHEVs together with ICE vehicles to be phased out because of their suboptimal environmental performance (Wappelhorst 2021). Following the same rationale, PHEVs receive less focus in this study.
- For heavy-duty trucks, this study covers LNG trucks given their increasing market popularity. Hybrid heavy-duty trucks are not considered because the fuel economy advantage of hybrid heavy-duty trucks is not evident for long-haul HDTs. In China, 47 percent of the daily VKTs of long-haul HDTs were fulfilled on highways (RIOH and Sinoiov 2021) with an average speed of 57 km per hour. The fuel savings of HDTs over highway cycles were only 3–6 percent compared with 30 percent fuel savings over city driving cycles (Gao et al. 2015). Further, limited hybrid models are available in China's market: There were only three hybrid models sold in 2020 (iCET 2021).
- For all the vehicle segments, biofuels are not considered. See Appendix C to learn why.

Second, the projected growth in NEV sales is likely to follow an S-curve (Abramczyk et al. 2017) whereby growth is slow when the technology is new, but as costs fall and infrastructure expands, a tipping point is reached and sales then grow exponentially. The S-curves differ by vehicle segment, with NEV buses reaching the tipping point and other segments still situated at the early stages of their S-curves (Table 10). This study uses the timing of total cost of ownership parity and public incentives to derive the possible tipping points for NEVs by vehicle segment.

Table 9 | **Progression along the S-Curve under the Stated Policy Scenario**

historic market share targeted market share

	PROGRESSION OF NEVs ALONG THE S-CURVE UNDER THE STATED POLICY SCENARIO	POLICY INCENTIVES FOR NEV ADOPTION	POLICY INCENTIVES FOR CHARGING/REFUELING INFRASTRUCTURE
Passenger cars	By 2025: NEVs will represent 20% of annual sales[a] By 2030: Clean-energy vehicles will represent 40% of annual sales[b] By 2035: NEV cars will account for 50–60% of annual car sales[c] 	▪ National NEV procurement subsidies; waived NEV purchase tax ▪ Fleet-average fuel consumption standard	▪ Waived demand charges for electric vehicle charging nationwide ▪ Local subsidies on charging facilities' CAPEX and/or O&M
Buses	From 2021: For air pollution control and ecological civilization pilot regions, no less than 80% of annual newly added or replaced buses should be NEVs[d] 	▪ National NEV procurement subsidies; waived NEV purchase tax ▪ National operation subsidies for e-buses	▪ Waived demand charges for electric vehicle charging nationwide ▪ Local subsidies on charging/hydrogen refueling facilities' CAPEX and/or O&M
Light-duty trucks	From 2021: For air pollution control and ecological civilization pilot regions, no less than 80% of annual newly added or replaced light-duty trucks should be NEVs[e] 	▪ National NEV procurement subsidies; waived NEV purchase tax ▪ Local operation subsidies in selected cities such as Shenzhen and Beijing ▪ Preferential city access policies in selected cities	▪ Waived demand charges for electric vehicle charging nationwide ▪ Local subsidies on charging/ hydrogen refueling facilities' CAPEX and/or O&M
HDTs	By 2030: Clean-energy vehicles will represent 40% of annual sales[f] By 2030: NEV trucks will account for more than 12% of annual truck sales[g] 	▪ National NEV procurement subsidies; waived NEV purchase tax ▪ Preferential access policies in some ports and industrial parks	▪ Waived demand charges for electric vehicle charging nationwide ▪ Local subsidies on charging/hydrogen refueling facilities' CAPEX and/or O&M

Notes: Although motorcycles are not classified as NEVs in China, this study assumes gasoline-powered motorcycles will be completely electric by 2035.
[a] State Council 2020. [b] NDRC 2021. [c] China SAE 2020. [d] State Council 2020. [e] State Council 2020. [f] NDRC 2021. [g] China SAE 2020.
Abbreviations: NEV = new electric vehicle; CAPEX = capital expenses; O&M = operations and maintenance; HDT = heavy-duty truck; e-buses = NEV buses.
Source: WRI authors, based on existing policies.

For passenger cars, evidence shows that the tipping point is approaching. For example, NEVs accounted for 20 percent of China's passenger car sales in November 2021 (CAAM 2021b), meeting the 20 percent target set in *China's New Energy Vehicle Industrial Development Plan for 2021 to 2035* five years early (State Council 2020). Further, without public subsidies, the TCO parity of BEVs and ICE private cars would be reached between 2024 and 2030,[xi] where compact cars would reach parity earlier (in 2024–25) and sport utility vehicles (SUVs) with large battery sizes would reach parity during 2025–30 (Lutsey et al. 2021; see Appendix B).

This study assumes the following:

- The growth curve of the NEV market share in the Stated Policy scenario aligns with the nonbinding targets set in *China's Technology Roadmap for Energy-Saving and New Energy Vehicles 2.0* (the *Roadmap*; China SAE 2020), where NEVs will account for 40 percent of passenger car sales by 2030, 50 percent by 2035, and 100 percent by 2060.

- The growth curve of the NEV market share in the Deep Electrification scenario aligns with the Paris Climate Agreement–compatible sectoral target, where BEVs are targeted to account for 100 percent of passenger car sales by 2035 (NCI and CA 2020). To achieve the Paris Agreement–compatible sectoral target, policy interventions such as enhanced fleet-wide fuel consumption standards, road access privileges, and increased infrastructure accessibility are necessary.

For buses, with tremendous public subsidies, even though the TCO of BEV buses has not achieved cost parity with diesel buses (World Bank 2021), NEV buses have gained momentum in the country, accounting for over 90 percent of the annual bus sales since 2016. Therefore, this study assumes NEV buses will account for 100 percent of the market share starting in 2021 across all scenarios.

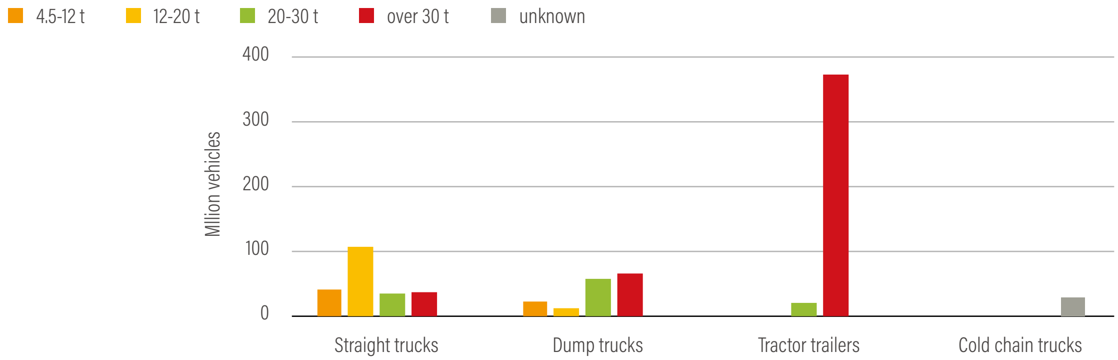
For light-duty trucks: Although the current 1 percent market share of NEV light-duty trucks is far from the 80 percent target set in China's *NEV Industrial Development Plan 2021–2035*, light-duty trucks are edging toward the tipping point. The return-to-base nature and limited daily mileage of light-duty trucks used for urban deliveries make them ideal for electrification following buses. For example, with subsidies and preferential road access policies, 100 percent of the annually registered light-duty trucks are now NEVs in Shenzhen. Even without subsidies, the TCO parity of BEV light-duty trucks and ICE light-duty trucks will be reached in 2024–25 (see Appendix B). Therefore, this study assumes 100 percent market share of NEVs would be possible from 2035 across all scenarios.

For heavy-duty trucks: Due to technology constraints,[xii] a fragmented trucking industry (Qiu et al. 2020), relatively late timelines for TCO parity (Mao et al. 2021), and a lack of policy incentives (Xue et al. 2019), NEV HDTs should reach the market tipping point later than other vehicle segments.

Within HDTs, vehicles of different payloads and applied in different duty cycles have varying decarbonization paces: Straight trucks and dump trucks commonly used for urban deliveries, drayage, and regional operations with daily mileages below 200 kilometers could be sooner transitioned to zero emissions (reaching TCO parity by 2023–25 in China), and for these types of trucks and duty cycles, BEV technology is sufficient. However, for long-haul HDTs (with daily mileages over 200 kilometers and sometimes up to 1,000 kilometers) and temperature-controlled refrigerated HDTs, the transition would occur more slowly (reaching TCO parity by 2030–35). For these types of trucks and duty cycles, FCEV technology would be needed (Mao et al. 2021; DOT 2021; Agora Energiewende 2020a; Ledna et al. 2022).

At present, China's statistical system does not classify HDTs by operational duty cycle. For simplicity, this study assumes that all tractor trailers weighing above 30 tonnes are long-haul vehicles, though straight trucks are also used for long-haul shipments in China. Given this assumption, long-haul HDTs and refrigerated HDTs represent about 50 percent of the current HDT fleet, while straight trucks and dump trucks used in short-range duty cycles represent the

Figure 16 | **Fleet Mix of Heavy-Duty Trucks by Gross Vehicle Weight and Type**



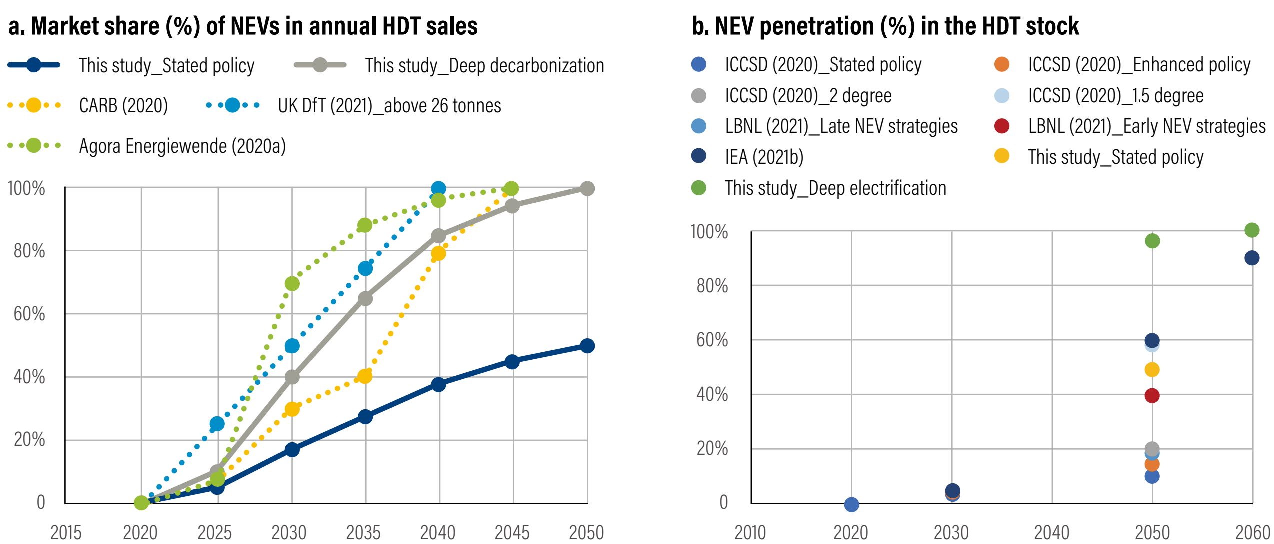
Abbreviation: t= tonne.
Source: Data are from a China Automotive Technology and Research Center (CATARC) database (accessed November 2021).

remaining 50 percent (Figure 16). This fleet mix is assumed to be stable over time.

In the Stated Policy scenario, although NDRC (2021) (the Action Plan) sets a mandatory target that clean-energy vehicles, which include NEVs and NG vehicles, represent 40 percent of annual vehicle sales in 2030, this target is ambiguous as to the specific share of NEVs for the truck segment. Therefore, the nonbinding targets set in the *Roadmap*, which were based on consultations with the truck manufacturing industry, are used in this study, where NEV trucks account for 17 percent of annual truck sales in 2030. This study further assumes that starting in 2050, all new HDTs operating in urban deliveries, drayage, and regional delivery duty cycles will be zero-emission vehicles, comprising 50 percent of HDT sales and 49 percent of the HDT stock.

In the Deep Electrification scenario, considering HDTs have 4–10 years of useful life (Mao et al. 2021), to achieve net zero by 2060, ICE HDTs (including diesel trucks and NG trucks) should stop being sold no later than 2050. This means not only 100 percent of the new HDTs operating in the urban delivery, drayage, and regional delivery duty cycles will be zero emissions, but also 100 percent of the new long-haul HDTs and refrigerated HDTs will be zero emissions from 2050 (Figure 17). For the latter, FCEV technology would be necessary. This ambitious

Figure 17 | **Projections for NEV Market Share and Fleet Penetration in Existing Studies**



Source: WRI authors; Agora Energiewende 2020a; IEA 2021b; LBNL 2021; UK DfT 2021; ICCSD 2020; CARB 2020.

target could be achieved through measures such as increasing vehicle acquisition subsidies (although China aims to phase out the national NEV purchase subsidies from 2023, subsidies to NEV HDTs should be maintained), introducing HDT operation subsidies, establishing fleet-wide fuel consumption standards for HDTs, adopting CO_2 emission–based road pricing, providing road access privileges for NEV HDTs, and improving infrastructure accessibility and convenience.

Fuel efficiency improvements

China is among the few developing countries with comprehensive and stringent requirements for vehicle fuel consumption (Table 10): Every vehicle manufactured in or imported to China is subject to the fuel consumption limits; further, vehicle original equipment manufacturers (OEMs) must meet the corporate average fuel consumption (CAFC) targets, where the accrued CAFC (and NEV) credits can be traded among OEMs under the *Parallel Management Regulation for CAFC and NEV Credits*.

With stricter requirements, China's fleet-average fuel consumption—that is, the average fuel consumption of all the cars registered in China including ICE vehicles and NEVs—has been improving. The fleet-average fuel consumption for passenger cars declined from 6.5 L/100 km (New European Driving Cycle) in 2016 to 5.61 L/100 km in 2020, approaching the 5 L/100 km target for 2020 (CATARC 2021). With the Phase V fleet-average fuel consumption target of 4 L/100 km for 2025—95 grams of CO_2 per kilometer (g/km) (Worldwide Harmonized Light Vehicles Test Procedure; WLTP)—China's fleet-average fuel consumption for passenger cars will be catching up with the EU's 95 g/km (WLTP) target for 2024 (EU P&C 2019).

Despite the improvement in fleet-average fuel consumption (including NEVs), the average fuel consumption for ICE vehicles alone has not significantly improved. This is because fleet-average fuel consumption is discounted by the increased NEV production, where OEMs meet the

Table 10 | **Compulsory Energy Efficiency Standards and Regulations in China**

	VEHICLE FUEL CONSUMPTION LIMIT	CAFC TARGET	NEV AND CAFC CREDITS
Passenger cars			
ICE vehicles	***4 L/100 km in 2025 (ICE vehicles and NEVs, WLTP)*** (As one of the Phase V fuel consumption standards for passenger cars, Fuel Consumption Limits for Passenger Cars [GB19578-2021])	***4 L/100 km in 2025 (ICE vehicles and NEVs, WLTP)*** (As one of the Phase V fuel consumption standards for passenger cars, Fuel Consumption Evaluation Methods and Targets for Passenger Cars [GB 27999-2019])	***18% credits are NEV credits*** (Phase 2 Parallel Management Regulation for CAFC and NEV Credits)
NEVs	***12 kWh/100 km in 2025 (BEVs, NEDC)*** (Electric Vehicles' Energy Consumption Limits [GB/T 36980-2018])		
NG vehicles	(None)	(None)	(None)
Light-duty commercial vehicles			
ICE vehicles	***20% reduction from Stage 2's level*** (Stage 3 Fuel Consumption Standard for Commercial Light-duty Vehicles [GB 20997-2015])	(None)	(None)
NEVs	(None)	(None)	(None)
NG vehicles	(None	(None)	(None)
Heavy-duty commercial vehicles			
ICE vehicles	***15% reduction from Stage 2's level*** (Stage 3 Fuel Consumption Standard for Commercial Heavy-duty Vehicles [GB 30510-2018])	(None)	(None)
NEVs	(None)	(None)	(None)
NG vehicles	(None)	(None)	(None)

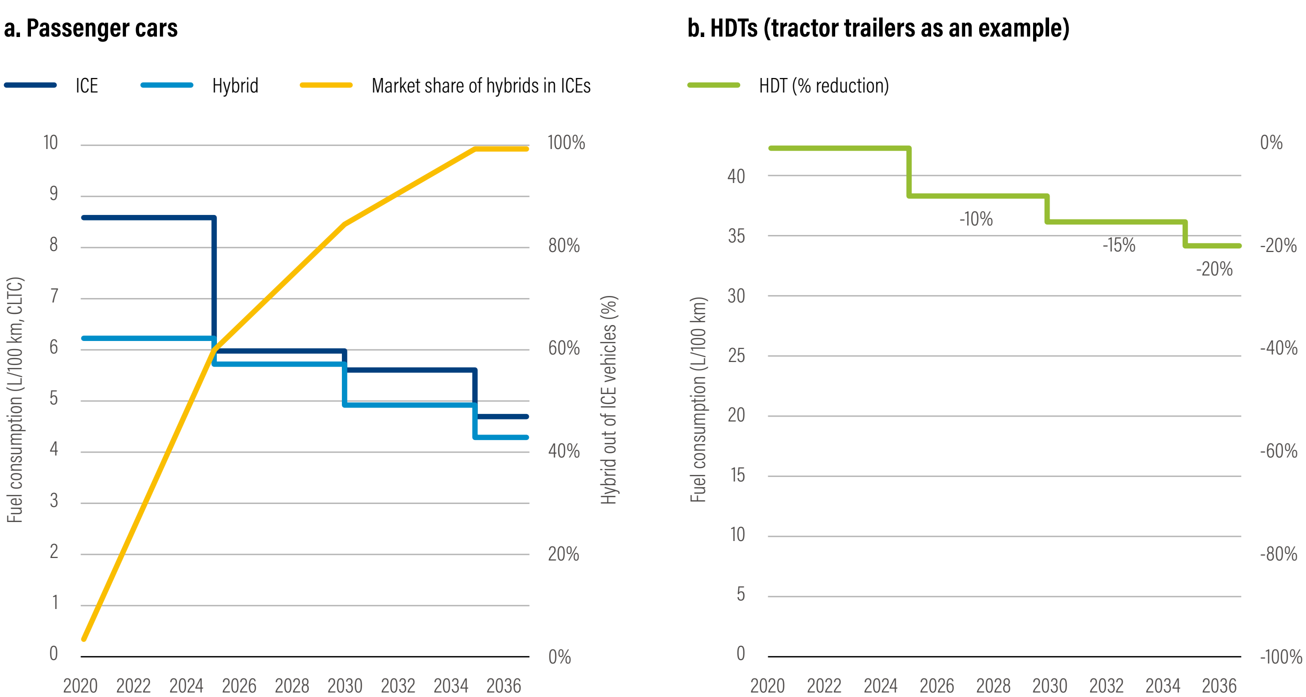
Abbreviations: CAFC = corporate average fuel consumption; NEV = new energy vehicle; ICE = internal combustion engine; NG = natural gas; BEV = battery electric vehicle; NEDC = New European Driving Cycle; WLTP = Worldwide Harmonized Light Vehicles Test Procedure; kWh = kilowatt-hour; km = kilometer; L = liter.
Source: WRI authors, based on existing policies and standards.

CAFC target by increasing the production of NEVs while not greatly improving ICE vehicles' fuel consumption levels (ICCT 2019). Consequently, although the fleet-average fuel consumption for passenger cars (including NEVs) in China dropped 13 percent from 2016 to 2020, the average fuel consumption for ICE vehicles decreased by only 7 percent (CATARC 2016, 2021).

In fact, ICE vehicles have an untapped potential for fuel consumption improvements. For passenger cars, the 4 L/100 km fleet-average target can be met by ICE vehicles alone. Particularly, hybrid vehicle adoption could be accelerated in China: In 2020, hybrid vehicles represented only 2.6 percent of car sales in China, behind the EU's 11.9 percent (ACEA 2021). According to the targets in the *Roadmap* set by industrial experts, hybrid cars would account for 50–60 percent of ICE car sales in 2025 and 100 percent in 2035 in China. For ICE HDTs, as predicted in the *Roadmap*, China can further reduce HDTs' fuel consumption by 20 percent in 2035 by improving aerodynamics and the thermal efficiency of engines, among other measures (Figure 18).

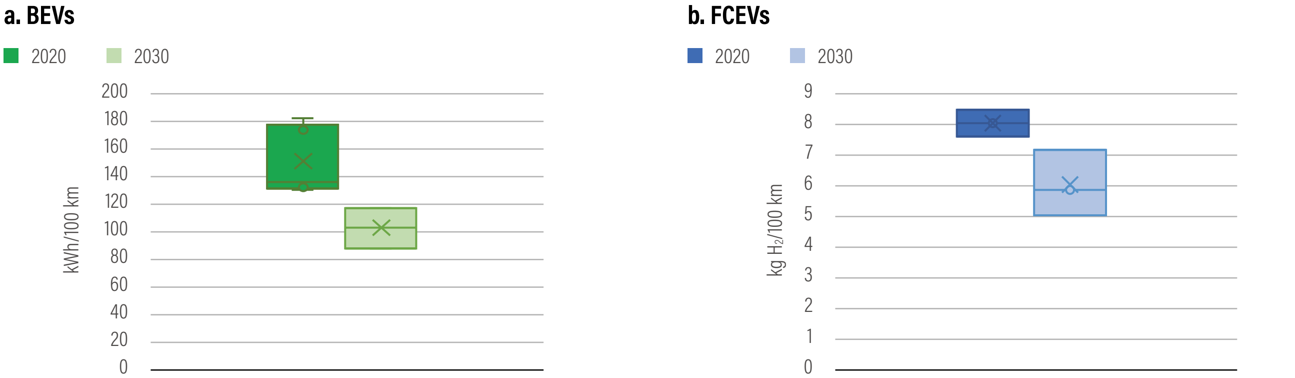
Energy efficiency improvements for NEVs are equally crucial (Gao et al. 2019). Although China established the world's first standard on electric vehicles' energy consumption limits for passenger NEVs, the energy efficiency of the commercial NEV fleet is unregulated. With increased gross vehicle weights (GVWs), some commercial NEVs have seen increases in energy consumption. For example, according to the *Annual Report on the Big Data of New Energy Vehicles in China (2021)* (Z.P. Wang et al. 2021), the fleet-average energy consumption of BEV buses in China increased by 10 percent from 2018 to 2020. Therefore, this study assumes future efficiency improvements will occur for commercial NEVs, with the degree of improvement based on a literature review—that is, the median values of energy consumption rates in existing studies (see Figure 19).

Figure 18 | **Fuel Consumption Improvement Targets in the *Roadmap* (2020–35)**



Abbreviations: HDT = heavy-duty truck; L = liter; km = kilometer; CLTC = China Light-Duty Vehicle Test Cycle; ICE = internal combustion engine; *Roadmap = China's Technology Roadmap for Energy-Saving and New Energy Vehicles 2.0.*
Source: China SAE 2020.

Figure 19 | **Energy Efficiency of New Energy Vehicle Tractor Trailers with Gross Vehicle Weights above 36 Tonnes in 2020 and 2030**



Abbreviations: GVW = gross vehicle weight; kWh = kilowatt-hour; km = kilometer; H_2 = hydrogen; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.
Sources: Mareev et al. 2018; Phadke et al. 2021; Liimatainen et al. 2019; T&E 2020b; F.Q. Liu et al. 2021; Mao et al. 2021.

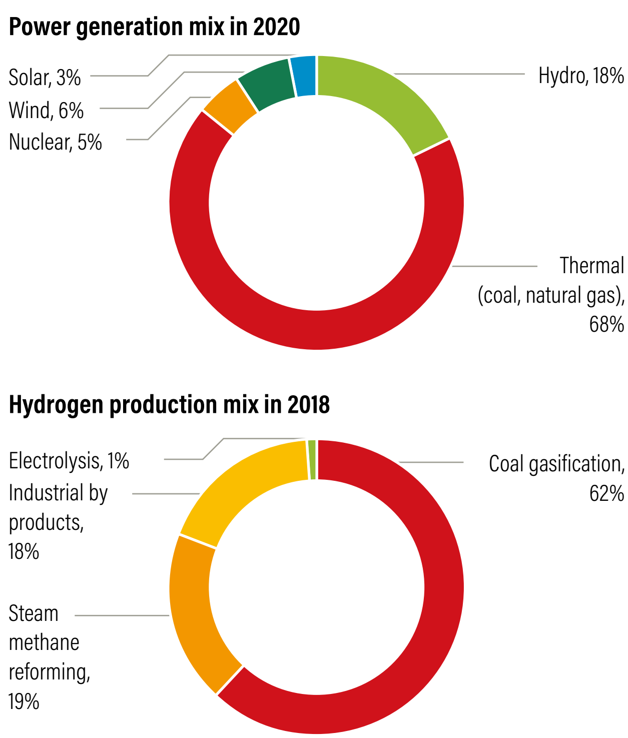
In this study, we used the nonbinding targets for ICE vehicles in the Stated Policy scenario. Considering the targets in the Stated Policy scenario are already ambitious, we developed the BAU scenario—with no fuel consumption improvements for ICE vehicles or NEVs—to reflect the case when the targets in the Stated Policy scenario are not met.

For this study, we used real-world fuel consumption instead of certified fuel consumption. Because type-approval driving cycles[xiii] differ from real-world driving conditions and vehicles with larger GVWs[xiv] are increasing in the fleet mix, the real-world fleet-average fuel consumption of ICE vehicles is larger than certified fuel consumption. From 2008 to 2017, China's real-world fleet-average fuel consumption for ICE cars was 8.6 L/100 km (iCET 2017), meaning that not only did real-world fuel consumption not improve over the past decade, but it was also 30% higher than certificated consumption. Therefore, to capture true fuel use, the study used the real-world fuel consumption estimated in COPERT (see Section 2.2.1) for the base year and assumed that, in the future, the gap between real-world fuel consumption and certified fuel consumption will close.

3.2.4 Grid and hydrogen decarbonization

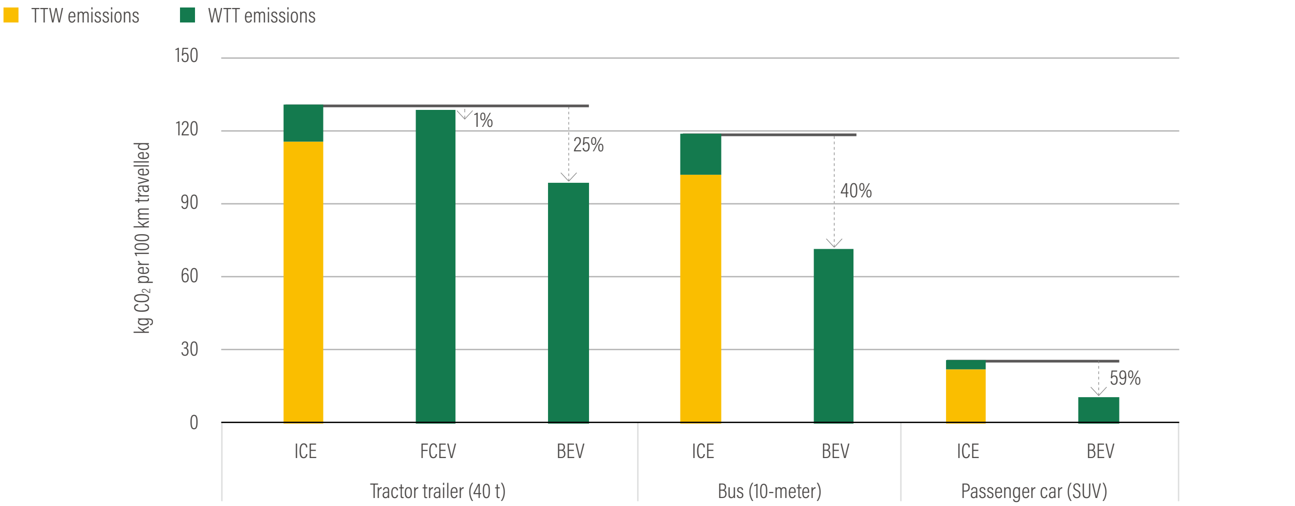
Because coal is the major feedstock for electricity and hydrogen generation in China, how electricity and hydrogen are generated play a role in road transport decarbonization. According to the China Electricity Council, nearly 61 percent of China's electricity generation was sourced from coal in 2020 (CEC 2020), compared with 37 percent of the power mix sourced from fossil fuels[xv] in the EU in the same year (Agora Energiewende 2020b); 62 percent of hydrogen was sourced from high-emitting coal gasification in 2018, compared with 95 percent of U.S. hydrogen production coming from steam methane reforming (DOE 2020; see Figure 20).

Figure 20 | **Current Power Mix and Hydrogen Production Mix in China**



Source: CEC 2020; CSI 2018.

Figure 21 | **WTW Emissions (TTW + WTT Emissions) of Different Powertrains by Vehicle Segment under the Current Power Mix (2020) and Hydrogen Production Mix (2018)**



Note:
- The energy consumption of tractor trailers is 34 L/100 km for ICE vehicles, 150 kWh/100 km for BEVs, and 8.5 kg/100 km for FCEVs. That of passenger cars (sport utility vehicles) is 8.6 L/100 km for ICE vehicles and 16.5 kWh/100 km for BEVs, and the energy consumption of buses is 38 L/100 km for ICE vehicles and 109 kWh/100 km for BEVs.
- WRI authors calculated WTT emission factors for petroleum and different hydrogen production processes based on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET 2.0) Model (ANL 2014). Emissions from transportation and distribution of hydrogen are not included. An 8 percent electricity transmission and distribution loss and charging loss is assumed for BEVs.

Abbreviations: WTW = well to wheel; TTW = tank to wheel; WTT = well to tank; CO_2 = carbon dioxide; km = kilometer; t = tonne; ICE = internal combustion engine; FCEL = fuel cell electric vehicle; BEV = battery electric vehicle; kWh = kilowatt-hour; kg = kilogram; L = liter.

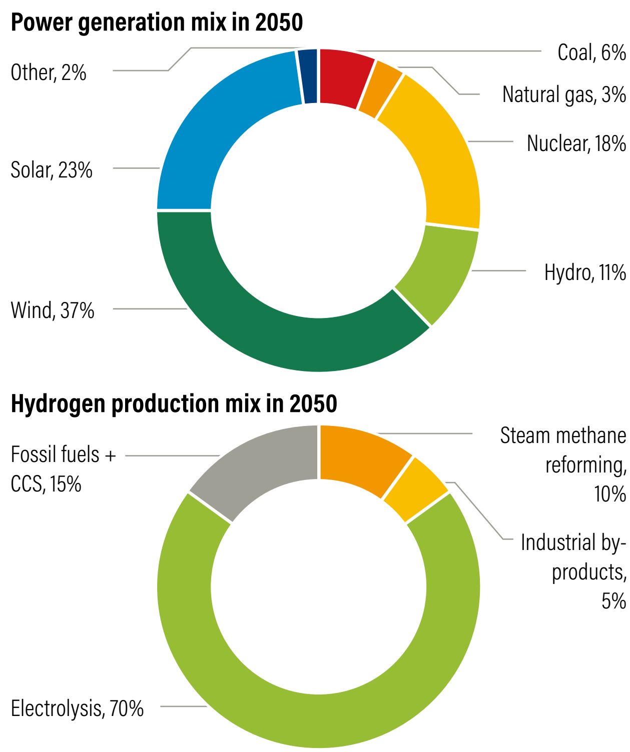
Source: WRI authors' calculations.

Because of China's heavy reliance on coal for power and hydrogen generation, the current decarbonization potential of NEVs is limited, particularly for the energy-intensive heavy-duty NEVs. Taking a 40-tonne tractor trailer as an example (see Figure 21), a BEV tractor trailer saves 25 percent WTW CO_2 emissions per 100 km travelled compared with the WTW emissions of ICE vehicles. These emissions savings are less than the 59 percent savings from a NEV passenger car versus an ICE passenger car. Further, the emissions savings for FCEVs are more insignificant: The WTW emissions from a FCEV tractor trailer are almost identical to the WTW emissions of an ICE tractor trailer and even 11 percent higher than the tailpipe emissions of an ICE tractor trailer.

To decarbonize the transport sector, the power sector and hydrogen-related industry must be decarbonized simultaneously. In the Stated Policy scenario, we used the existing decarbonization roadmaps announced in China's policy directives and those proposed by industrial alliances (Figure 22):

- Power sector decarbonization roadmap: In the near term, according to NDRC (2021),

Figure 22 | **Power Mix and Hydrogen Production Mix Based on China's Current Commitments**



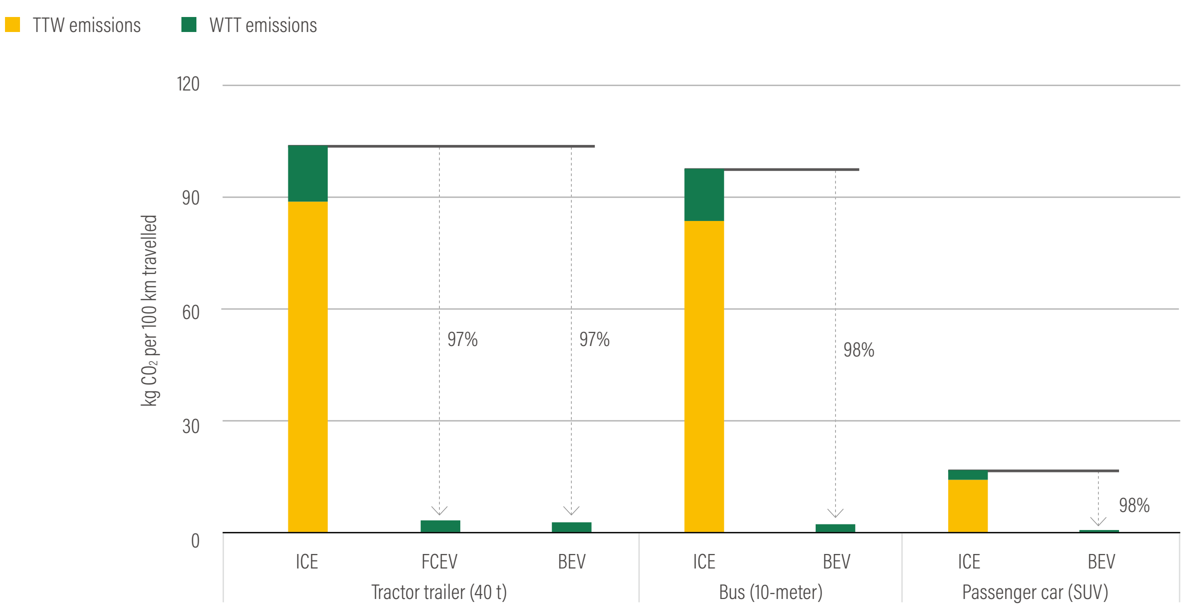
Abbreviation: CCS = carbon capture and storage.
Source: ICCSD 2020; CHA 2019.

China's coal consumption will peak in the 14th five-year period (2021–25), and the installed capacities of wind and solar will reach over 1,200 gigawatts. Over the long term, based on *China's Long-Term Low-Carbon Development Strategies and Pathways* (ICCSD 2020), coal should represent 6.5 percent of China's power generation by 2050.

- Hydrogen generation decarbonization roadmap: As outlined in the *White Paper on China's Hydrogen Energy Carrier and Fuel Cell Stack Industry* (CHA 2019), the market share of China's domestic green hydrogen (water electrolysis using 100 percent renewable energy) production will grow from 1 percent in 2020 to 70 percent in 2050. The share of domestic gray hydrogen production will drop to 15 percent, in which steam methane reforming and industrial by-products will respectively represent 10 percent and 5 percent. Coal gasification facilities will be completely decommissioned before 2050.

The stated policies are already ambitious. If these targets for power mix and hydrogen production mix can be met, WTW emissions of NEVs will drop to nearly zero in 2050 (see Figure 23). As a benchmark, a less-ambitious BAU scenario (see Table 11) helps us evaluate the emission reduction potential of the stated policies and the consequences of not meeting these targets. In the BAU scenario, a fraction of fossil fuels would remain in power generation (25 percent) and hydrogen production processes (50 percent) (F.Q. Liu et al. 2021).

Figure 23 | **Emissions of Different Powertrains by Vehicle Segment under the Power Mix and Hydrogen Production Mix in the Stated Policy Scenario**



Notes: WRI authors calculated WTT emission factors for different hydrogen production processes using the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET 2.0) Model (ANL 2014).
Abbreviations: kg CO_2 = kilograms of carbon dioxide; ICE = internal combustion engine; FCEV = fuel cell electric vehicle; BEV = battery electric vehicle; t = tonne; SUV = sport utility vehicle; TTW = tank to wheel; WTT = well to tank.
Source: WRI authors' calculations.

Table 11 | **Power Mix and Hydrogen Production Mix under Different Scenarios**

	2050	
	BUSINESS AS USUAL	**STATED POLICY**
Power generation mix	• Coal and natural gas (25%) • Non-fossil fuel (75%)	• Coal and natural gas (9%) • Non-fossil fuel (92%)
Hydrogen production mix	• Gray hydrogen: coal gasification (15%), steam methane reforming (SMR) (15%), industrial by-products (5%) • Blue hydrogen: fossil fuels, carbon capture and storage (CCS) (15%) • Green hydrogen: renewable energy electrolysis (50%)	• Gray hydrogen: SMR (10%) and industrial by-products (5%) • Blue hydrogen: fossil fuels and CCS (15%) • Green hydrogen: renewable energy electrolysis (70%)

Source: Hydrogen production mix for the Business as Usual scenario is based on WRI authors' assumptions. The rest of the values come from ICCSD (2020) and CHA (2019).

3.2.5 Summary

We modelled five scenarios in this study: the Business as Usual scenario, the Stated Policy scenario, and three enhanced scenarios—Structural Change, Deep Electrification, and Deep Decarbonization (Table 12).

The BAU scenario is a counterfactual scenario, featured by no improvements in energy efficiency and limited degrees of vehicle electrification. This scenario helps evaluate the decarbonization potential of the country's stated policies by revealing the consequences of not achieving them.

The Stated Policy scenario projects emissions based on the intermediary targets and policies planned by the national government and nonbinding targets proposed by industrial associations. As demonstrated in Sections 3.2.3 and 3.2.4, the stated policies are ambitious for fuel efficiency improvement measures and power-sector and hydrogen-related-sector decarbonization, but less ambitious for structural changes and vehicle electrification. Therefore, in addition to the Stated Policy scenario ("Stated_policy"), we constructed three forecasting scenarios:

- The Structural Change scenario ("Low_stock") is based on the Stated_policy scenario but assumes greater degrees of mode shift and vehicle occupancy improvements. As a result, the scenario is characterized by smaller vehicle stocks.

- The Deep Electrification scenario ("DeepELE") is based on the Stated_policy scenario but involves a more rapid diffusion of NEVs—that is, NEVs will represent 100 percent of passenger car sales by 2035 and 100 percent of HDT sales (including long-haul HDTs and refrigerated HDTs) by 2050.

- The Deep Decarbonization scenario ("DeepDecarb") is based on the Stated_policy scenario but integrates the Low_stock and DeepELE scenarios. Therefore, the scenario represents the most ambitious case that is conducive to attaining China's carbon neutrality target.

Table 12 | **Key Parameters in the Five Scenarios**

	2020	BUSINESS AS USUAL (BAU)	STATED POLICY (Stated_policy)	STRUCTURAL CHANGE (Low_stock)	DEEP ELECTRIFICATION (DeepELE)	DEEP DECARBONIZATION (DeepDecarb)
Demand and structural change						
Passenger car stock in 2020 and 2060 (million vehicles)	239 (170 cars per 1,000 persons)	506 (425 cars per 1,000 persons)	506	381 (300 cars per 1,000 persons)	506	381
Freight tkm in 2020 and 2060 (trillion tkm)	11.2	25.9				
Freight mode share in 2020 and 2060 (% of road freight in domestic tkm)	54%	50%	50%	40%	50%	40%
Freight average load in 2020 and 2060 (tonnes per vehicle kilometer)	9.5	9.5	9.5	11.5	9.5	11.5
HDT stock in 2020 and 2060 (million vehicles)	9.5	20	20	12	20	12
Vehicle electrification						
Passenger car electrification in 2020 and 2035 (% of NEVs in passenger car sales)	15.7%	30%	50%	50%	100%	100%
HDT electrification in 2020 and 2050 (% of NEVs in HDT sales)	0.6%	12%	50% (only the HDTs operating in urban deliveries, drayage, and regional delivery duty cycles)	50% (only the HDTs operating in urban deliveries, drayage, and regional delivery duty cycles)	100% (all the HDTs, including long-haul and refrigerated HDTs)	100% (all the HDTs, including long-haul and refrigerated HDTs)
Fuel efficiency						
ICE passenger cars	Fleet average: 5.6 L/100 km Hybrid: 2.6% of car sales	No improvement	Fleet average: 4 L/100 km Hybrid: 60% of car sales in 2025, 100% in 2035			
ICE HDTs	*(Depends on gross vehicle weight)*	No improvement	HDTs: 20% improvement in 2035			
NEVs	*(Depends on gross vehicle weight)*	No improvement	(Various degrees of improvement based on gross vehicle weight)			
Grid and hydrogen decarbonization						
Power mix in 2020 and 2050 (% of non-fossil fuels in power mix)	32%	75%	92%			
Hydrogen mix in 2020 and 2050 (% of gray hydrogen in production mix)	99%	35%	15%			

Source: WRI authors' assumptions.

CHAPTER 4

MODEL RESULTS

This chapter includes our projections for China road transport's GHG emissions, energy usage, petroleum consumption, and air pollutant emissions up to 2060 under different scenarios. It also evaluates the decarbonization and air pollution reduction potentials of different measures and identifies what policies are cost effective to meet China's 2060 carbon neutrality commitment.

4.1 Base Year Calibration

The base year of the study is 2020, when the most recent statistical data are available. Despite the decrease in transport activities and emissions during the forced lockdown period for COVID-19 from February to April 2020 (Le Quéré 2020), China experienced only slightly affected road freight volumes, increased private car purchases, and temporarily lower transit ridership during that time (Zhou et al. 2020).

Using the bottom-up approach (see Section 2.2), we estimated the base year's GHG emissions. We verified the results with the top-down estimates that were derived based on the fossil fuel consumption from China's energy balance using the methodology outlined in Su (2017). We reconciled the difference between the top-down and bottom-up estimates by adjusting vehicle kilometers travelled, following the recommended procedure in IPCC (2006).

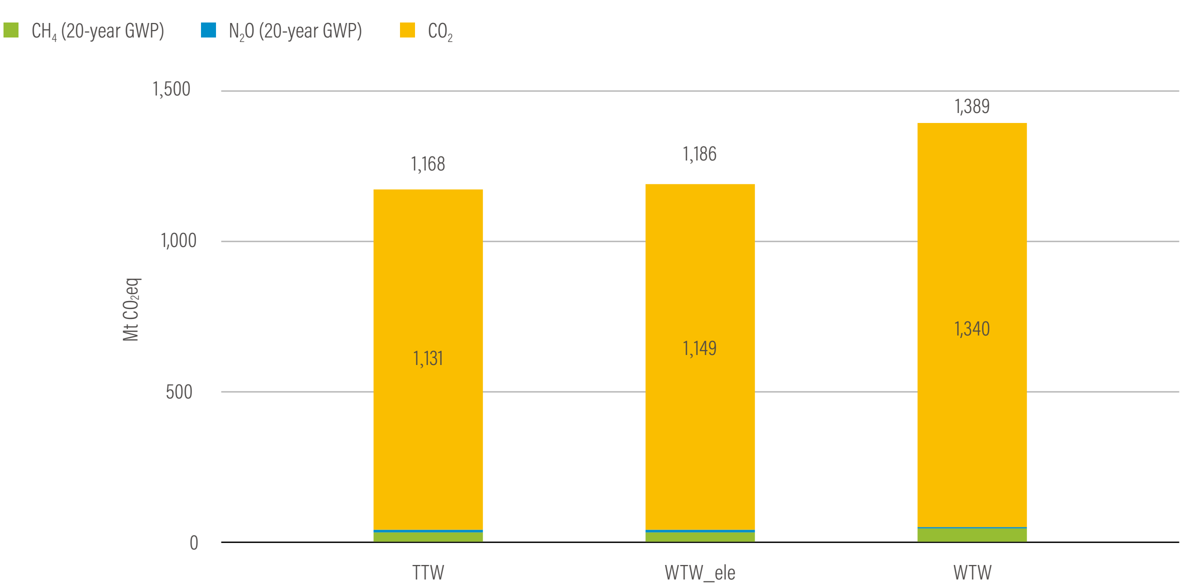
For the base year, we calculated and compared the GHG emissions of three emissions scopes: TTW GHG emissions (the emissions from vehicle operations), WTW_ele emissions (the TTW emissions and upstream emissions from the production of electricity and hydrogen), and the full scope of WTW emissions.

The results show the following: TTW GHG emissions were 1,168 Mt CO_2eq in 2020, almost identical to the WTW_ele emissions (1,186 Mt CO_2eq) (Figure 24). This is due to limited NEV penetration now. In contrast, the full scope of WTW GHG emissions was 19 percent higher than TTW emissions as emissions from the oil refinery and gas processing industries are included in WTW emissions. Regardless of the emissions scope, CO_2 accounted for the majority (96–97 percent) of the GHG emissions.

Contributions to GHG emissions and air pollutants varied across vehicle segments (see Figure 25):

- CO_2 emissions: With a large fleet size (70 percent of the vehicle stock), private cars contributed the largest share of WTW_ele CO_2 emissions (40 percent). Following private cars were heavy-duty trucks (35 percent of CO_2 emissions) and light-duty trucks (17 percent of CO_2 emissions). Notably, heavy-duty trucks' 35 percent CO_2 emissions contribution is disproportionate to its relatively small fleet size (3 percent of the vehicle

Figure 24 | **GHG Emissions from China's Road Transport Sector in 2020**



Notes: Greenhouse gases include carbon dioxide, nitrous oxide (N_2O), and methane (CH_4). N_2O and CH_4 use 20-year global warming potential (GWP) values from IPCC (2014).
Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; TTW = tank to wheel; WTW_ele = TTW emissions and upstream emissions from the production of electricity and hydrogen; WTW = well to wheel.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Figure 25 | **Breakdowns of Vehicle Stocks, GHG Emissions, and Air Pollutants in 2020**

Notes: Abbreviations: CO_2 = carbon dioxide; LDT = light-duty truck; HDT = heavy-duty truck; WTW_ele = tank to wheel emissions and upstream emissions from the production of electricity and hydrogen; CH_4 = methane; N_2O = nitrous oxide; NOx = nitrogen oxides; PM = particulate matter; NMHC = non-methane hydrocarbons; CO = carbon monoxide.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

stock). Although motorcycles represented 20 percent of the vehicle stock, their corresponding CO_2 emissions were insignificant.

- CH_4 emissions: High methane emissions were observed for fleets with relatively large shares of NG vehicles, including heavy-duty trucks (51 percent), buses (18 percent), and taxis (15 percent). This is because of the high methane emissions typically associated with NG vehicles (Pan et al. 2020).
- N_2O emissions were primarily attributable to diesel vehicles—heavy-duty trucks (51 percent) and light-duty trucks (21 percent).
- Air pollutants: Private cars contributed the largest share of CO (40 percent) and NMHC (60 percent) emissions, and fossil fuel–powered motorcycles' NMHC emissions were also considerable (13 percent). Heavy-duty trucks and light-duty trucks were the major sources of toxic NOx and PM emissions.

4.2 Scenario Projections

This section includes our projections for WTW_ele GHG emissions, energy usage, petroleum consumption, and air pollutant emissions up to 2060 under different scenarios.

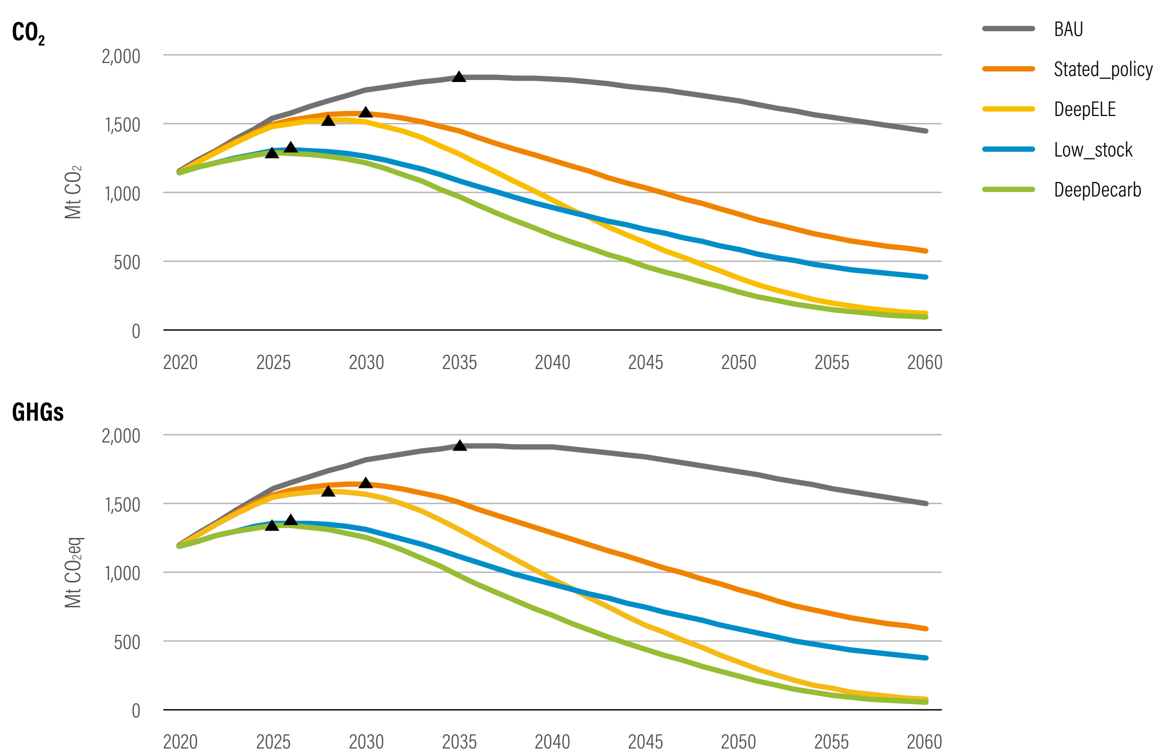
We did not consider the full scope of WTW emissions because decarbonizing the oil refinery and gas processing industries is difficult and involves different policy recommendations. However, we did consider emissions from the production of electricity and hydrogen because it is still unclear if switching to electricity and hydrogen should count as low carbon when power and hydrogen production is not decarbonized (Gustafsson et al. 2021).

4.2.1 GHG emissions

Results from the scenario analysis suggest the following (see Figure 26 and Table 13):

In the near term, the growth in road transport GHG emissions should continue. The likely peak

Figure 26 | Carbon Dioxide and Greenhouse Gas Emission Projections under Different Scenarios



Note: Greenhouse gases include carbon dioxide, nitrous oxide, and methane. Nitrous oxide and methane use 20-year global warming potential values from IPCC (2014).
Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; CO_2 = carbon dioxide; GHGs = greenhouse gases; BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Table 13 | **Carbon Dioxide Emissions and Greenhouse Gas Emissions in the Peak Year and in 2060 under Different Scenarios**

	PEAK YEAR		PEAK EMISSIONS (Mt CO_2eq)		2060 EMISSIONS (Mt CO_2eq)		CUMULATIVE EMISSIONS (2020–60) (Mt CO_2eq)	
	CO_2	GHGs	CO_2	GHGs	CO_2	GHGs	CO_2	GHGs
BAU	2035	2035	1,867 (63%)[a]	1,909 (61%)	1,455 (27%)	1,495 (26%)	68,228	69,947
Stated_policy	2030	2030	1,598 (39%)	1,638 (38%)	556 (-52%)	595 (-50%)	46,910	48,615
DeepELE	2028	2028	1,546 (35%)	1,585 (34%)	88 (-92%)	88 (-93%)	35,818	36,518
Low_stock	2026	2026	1,322 (15%)	1,358 (15%)	360 (-69%)	384 (-68%)	36,080	37,268
DeepDecarb	2025	2025	1,301 (13%)	1,340 (13%)	63 (-95%)	63 (-95%)	28,643	29,205

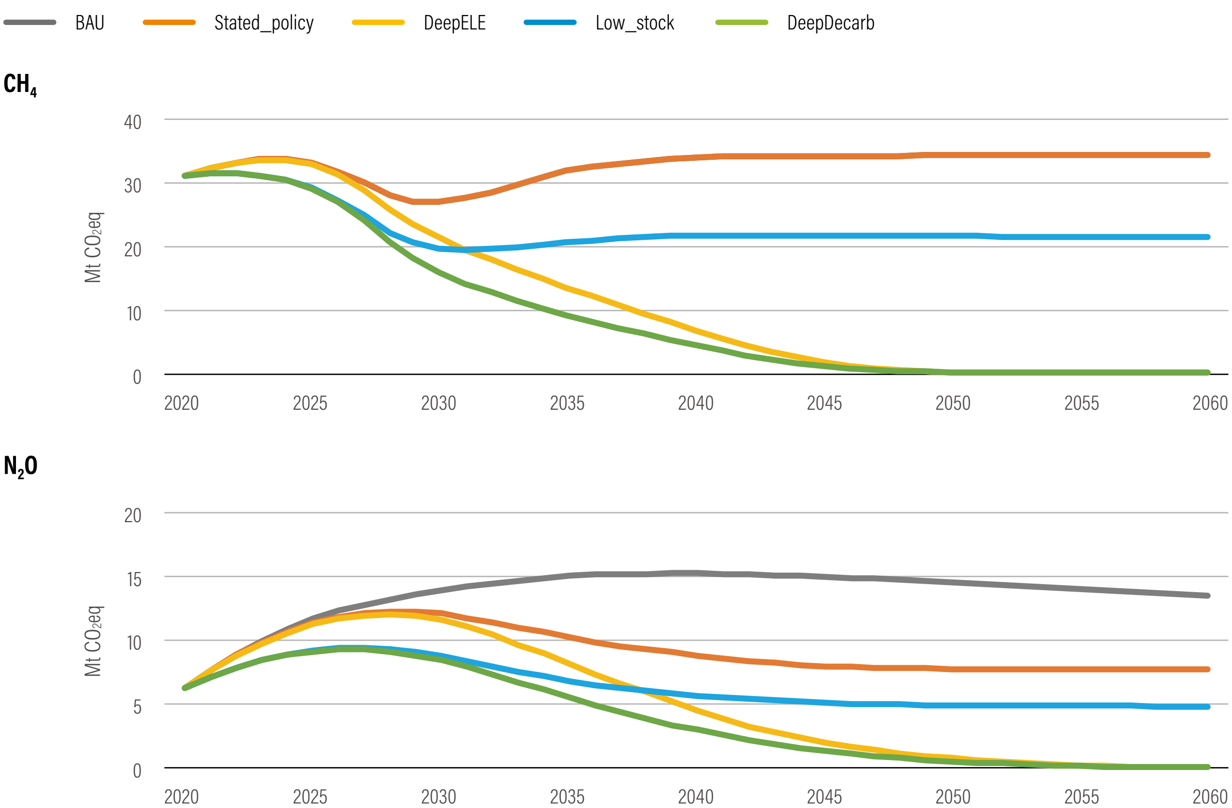
Notes: [a] Parentheses denote the change in emissions compared with the level in 2020. Color green denotes the emissions are lower than the 2020's level, while red denotes the emissions are higher than the 2020's level.
Abbreviations: CO_2 = carbon dioxide; GHG = greenhouse gas; Mt CO_2eq = million tonnes of carbon dioxide equivalent; BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

years of road transport's GHG emissions are between 2025 and 2035, with peak GHG emissions ranging from 1,340 Mt CO_2eq (13 percent increase from 2020) to 1,909 Mt CO_2eq (61 percent increase from 2020). The Stated_policy scenario suggests that if China implements the stated policies outlined by the government and targets set by industrial associations, the road transport sector's GHG emissions are likely to peak by 2030 at 1,638 Mt CO_2eq. The Low_stock and DeepELE scenarios indicate that with enhanced measures such as structural changes and vehicle electrification, the peak year would be advanced to 2026 and 2028, respectively, and peak GHG emissions would be lower—1,358 Mt CO_2eq and 1,585 Mt CO_2eq, respectively. Of note is that in the near term, structural changes are more effective at peaking emissions earlier and reducing emissions to a greater extent than vehicle electrification.

In the long term, GHG emissions in 2060 vary widely based on the scenario, ranging from 63 Mt CO_2eq (a 95 percent decrease from 2020) to 1,495 Mt CO_2eq (a 26 percent increase from 2020). Among the policy scenarios, the Stated_policy scenario shows that if the stated policies are effectively implemented over time, China's road transport GHG emissions would be 50 percent lower than in 2020. If additional measures such as structural changes and higher degrees of vehicle electrification are taken, as assumed with the DeepDecarb scenario, road transport emissions could be mitigated by 95 percent compared with 2020's level. Over the long term, vehicle electrification would surpass structural changes to become the measure with the highest decarbonization potential.

CH_4 and N_2O demonstrate slightly different pathways because both CH_4 and N_2O are not only GHG emissions, but also regulated air pollutants, subject to China's vehicle exhaust emission standards. Unlike other pollutants (See Section 4.2.3 and Figure 27), in the BAU scenario, neither CH_4 emissions nor N_2O emissions decline significantly after the implementation of the

Figure 27 | **Methane and Nitrous Oxide Emissions Projections under Different Scenarios**



Notes: Nitrous oxide and methane use 20-year global warming potential values in IPCC (2014).
Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; CH_4 = methane; N_2O = nitrous oxide; BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

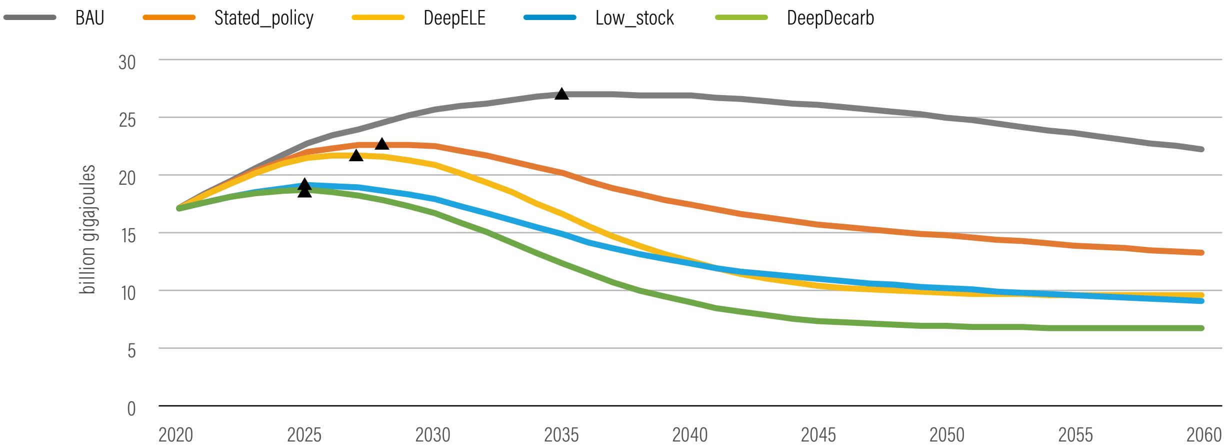
China 6 standard in 2020: CH_4 emissions initially drop from 2020 to 2030 due to the enforcement of China 6 but rebound after 2030 because the increasing adoption of NG vehicles offsets the decrease in per-vehicle NG emissions; the limited drop in N_2O emissions occurs because the deployment of aftertreatment systems in diesel vehicles to meet China 6's NOx emissions limit would lead to increased N_2O emissions (Clairotte et al. 2020). Therefore, as suggested by the DeepELE and DeepDecarb scenarios, in addition to relying on tightening emission exhaust standards, vehicle electrification can control CH_4 and N_2O emissions.

4.2.2 Energy demand

Energy demand in the road transport sector will experience drastic changes, both in terms of absolute energy volumes and the energy mix. The increased penetration of NEVs will substantially cut road transport's demand for fossil fuels (gasoline, diesel, and natural gas) (see Figures 28 and 29):

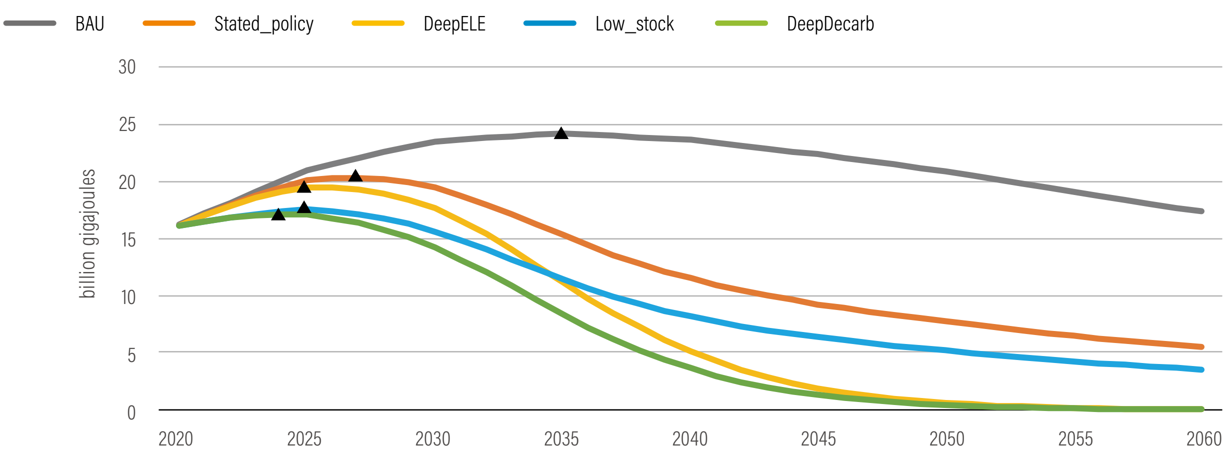
- Petroleum demand could peak earlier than the 2030 target set in NDRC (2021). In the Stated_policy scenario, the country's petroleum demand will peak in 2027, the same peak year for global petroleum demand forecasted by BloombergNEF (2021). The peak year would occur even sooner (2024–25) in the Low_stock, Deep_ELE, and DeepDecarb scenarios with reinforced decarbonization measures such as structural changes and vehicle electrification. In all the policy scenarios, petroleum consumption in 2060 would be 66–100 percent lower than in 2020, showing that the country's road transport sector will be less dependent on petroleum (petroleum use would be fully eliminated in 2060 in the Deep_ELE and DeepDecarb scenarios).

Figure 28 | **Total Energy and Petroleum Consumption in the Road Transport Sector**



Abbreviations: BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Figure 29 | **Petroleum Consumption in the Road Transport Sector**



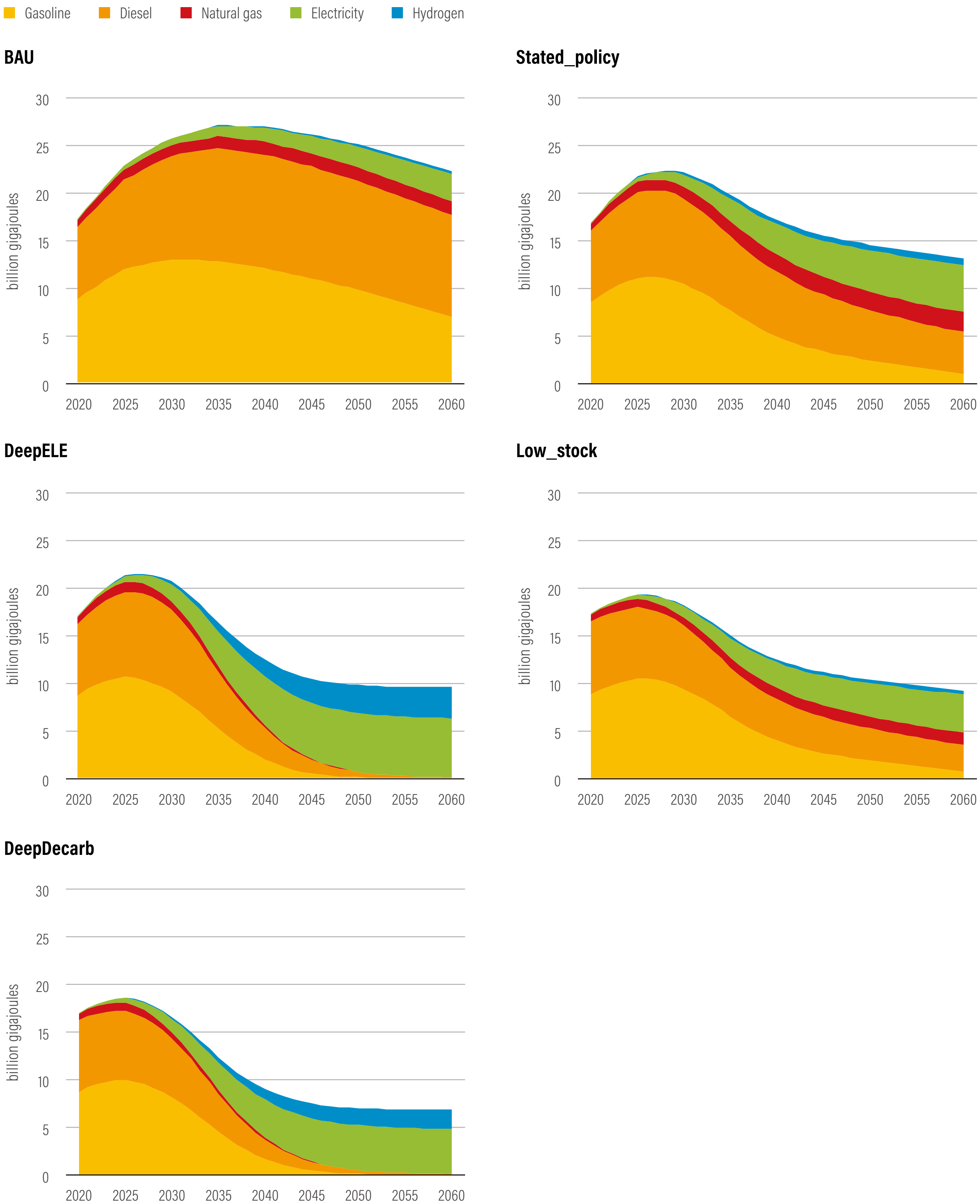
Abbreviations: BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

- Future demand for natural gas is more precarious: If NG vehicles play a significant role in meeting the clean energy vehicle sales target of 40 percent in 2030, the demand for natural gas will peak in 2060, with peak demand a 179 percent increase over 2020's level (see the Stated_policy and Low_stock scenarios); if NG vehicles are not recommended and are soon displaced by NEVs, the demand for natural gas would peak in 2024–26 and follow petroleum's path to be eliminated in 2060 (see the Deep_ELE and DeepDecarb scenarios).

By contrast, the growth in electricity and hydrogen demand would follow a strong upward trend. The electricity demand in 2060 varies between 2.8 billion gigajoules (GJ) and 6.2 billion GJ, and hydrogen demand between 0.4 billion GJ and 3.3 billion GJ (Figure 30).

Noteworthy is that a smaller NEV fleet would lead to less electricity and hydrogen demand. In the DeepDecarb scenario, electricity consumption in 2060 would be 24 percent lower and hydrogen demand 39 percent lower than in the DeepELE

Figure 30 | **Energy Demand Breakdowns under Different Scenarios**



Abbreviations: BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model

Table 14 | **Energy Demand in the Peak Year and in 2060 under Different Scenarios**

	PEAK YEAR FOR PETROLEUM	PEAK YEAR FOR NATURAL GAS	PETROLEUM (billion GJ)		NATURAL GAS (billion GJ)		ELECTRICITY (billion GJ)	HYDROGEN (billion GJ)
			PEAK	2060	PEAK	2060	2060	2060
BAU	2035	2060	24.7	17.4	1.4	1.4	2.8	0.4
			+52%	+7%	+97%	+97%	+2,500%	+401,400%
Stated_policy	2027	2060	20.4	5.49	2.0	2.0	5.0	0.7
			+26%	-66%	+179%	+179%	+4,500%	+659,900%
DeepELE	2025	2026	19.7	0.0	1.1	0.0	6.2	3.3
			+22%	-100%	+52%	-100%	+5,600%	+3,299,900%
Low_stock	2025	2060	17.7	3.5	1.3	1.3	3.9	0.4
			+9%	-78%	+71%	+71%	+3,500%	+399,900%
DeepDecarb	2024	2024	17.5	0.0	0.0	0.0	4.7	2.0
			+8%	-100%	-100%	-100%	+4,200%	+2,019,900%

Notes: Fossil fuels include gasoline, diesel, and natural gas. The peak years for petroleum (gasoline and diesel) are the same as the peak years for fossil fuels. The percentage denotes the level of emissions in comparison to that in 2020. Color green denotes the emissions are lower than the 2020's level, while red denotes the emissions are higher than the 2020's level.
Abbreviations: GJ = gigajoules; BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

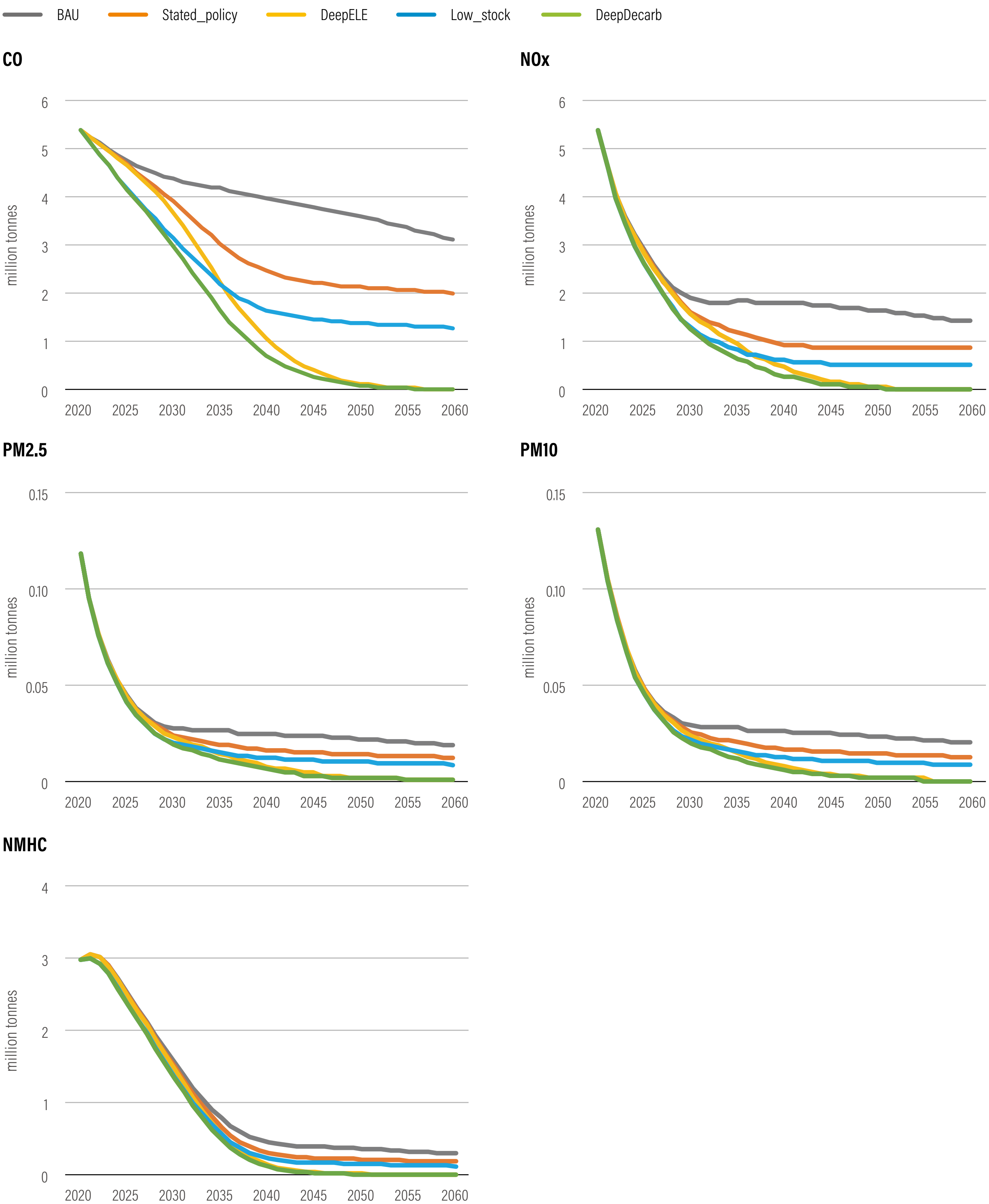
scenario (see Table 14). Therefore, managing vehicle ownership and usage is critical to lessening investments in installed capacity for power and hydrogen generation.

4.2.3 Air pollutants

Unlike GHG emissions and energy consumption, future emissions from air pollutants would keep declining across all the scenarios that decouple from GHG emission trajectories (see Figure 31).
Even under the BAU scenario, all the regulated air pollutants exhibit varying degrees of reduction, in which NOx emissions in 2060 decline by 73 percent from the 2020 level, PM by 84 percent, NMHC by 90 percent, and CO by 41 percent. This is mainly attributable to the enforcement of the China 6 standard for all vehicles starting in 2021 and the increasing adoption of end-of-pipe control measures (see Box 2). If the China 6 standard is not enforced, China will experience growing NOx, NMHC, and CO emissions (Figure 32).

Although nationwide, air pollutants from the road transport sector will be effectively controlled, sustained pollution abatement efforts are needed for a few reasons. First, air pollutants are local, and it is likely that regions with dense populations would still be exposed to significant vehicular emissions and high health risks. With the World Health Organization's new and stricter Global Air Quality Guidelines (WHO 2021), China's battle against air pollution is expected to continue. Second, besides the road transport sector, non-road transport sectors such as shipping and non-road machinery are also primary sources of air pollutants that require attention (Feng et al. 2019; Shao 2021). Third, although we did not consider any next-generation China exhaust emission standard (such as a Euro 7 equivalent) or an ultra-low emissions requirement for NOx emissions (see Box 2), the benefits of a tougher standard on NEV promotion and air quality improvement should not be underrated by policymakers (ACEA 2022).

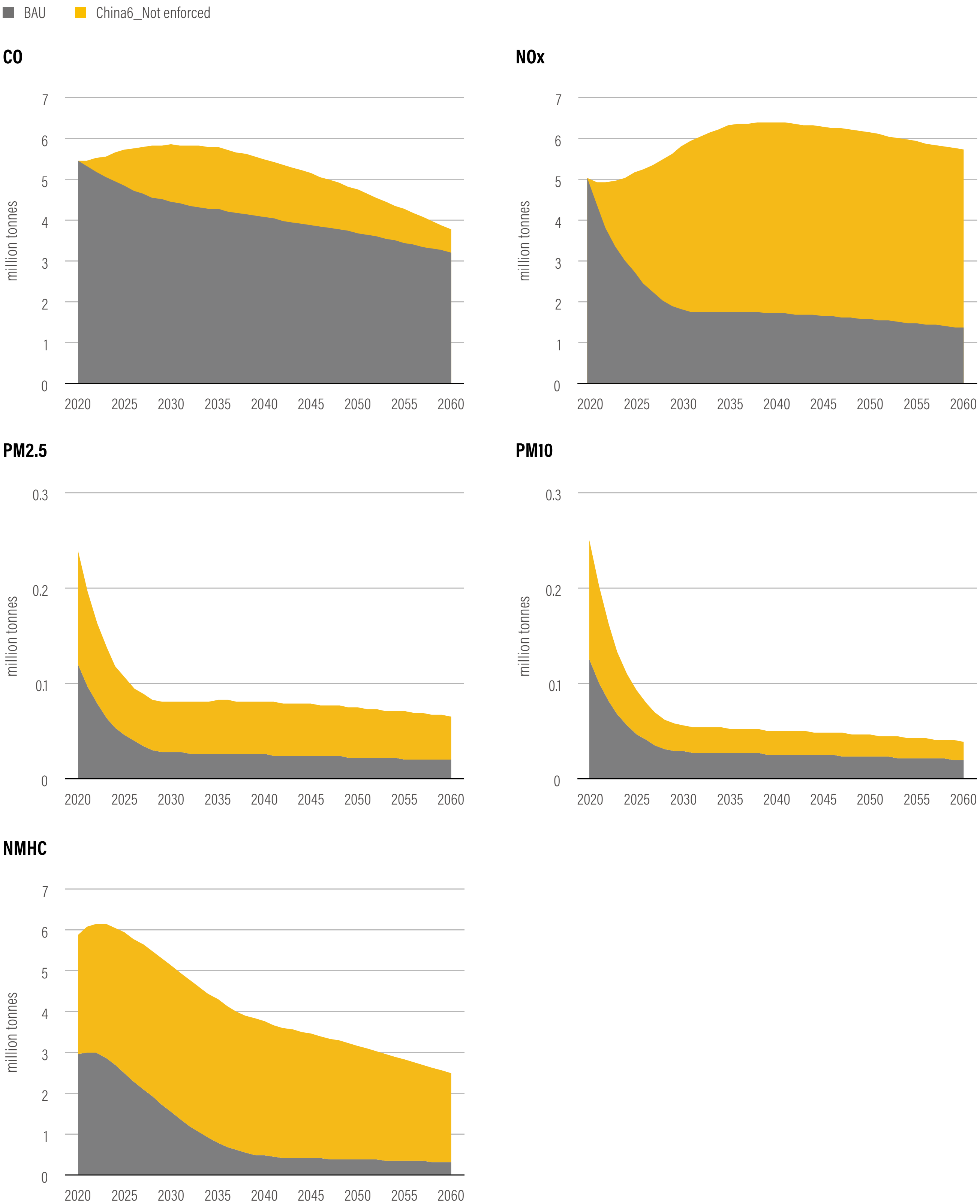
Figure 31 | **Air Pollutant Emissions from the Road Transport Sector**



Abbreviations: CO = carbon monoxide; NOx = nitrogen oxides; PM2.5 = particulate matter 2.5 micrometers or less in diameter; PM10 = particulate matter 10 micrometers or less in diameter; NMHC = non-methane hydrocarbons; BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low_stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.

Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Figure 32 | **Air Pollutant Reductions Resulting from the Introduction of China 6 Standard**



Abbreviations: CO = carbon monoxide; NOx = nitrogen oxides; PM2.5 = particulate matter 2.5 micrometers or less in diameter; PM10 = particulate matter 10 micrometers or less in diameter; NMHC = non-methane hydrocarbons; BAU = Business as Usual scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Box 2 | China's End-of-Pipe Emission Control Standards

China's vehicle exhaust emission standards have evolved rapidly over the past 20 years from China 1 to China 6. Now, China 6 is one of the most stringent emission standards in the world, with the air pollutant limits in China 6a (the standard for light-duty vehicles was effective as of 2020, and that for heavy-duty trucks as of 2021) equating to those of Euro 6 (see Figure B2.1 for an example of limits for diesel HDTs). After China 6b becomes effective in 2023, the emission limits will be even lower than those in Euro 6.[a]

However, other global emission regulations show that there is still room for improvement in China's emission standard. For example, compared with the NOx limit (0.27 g/kWh) mandated by the United States' 2010 emission standard for HDTs, China 6's limit (0.4 g/kWh) is still on the higher end. Further, with California's adoption of the *Heavy-Duty Engine and Vehicle Omnibus Regulation* in 2020, which mandates a further 90 percent reduction of NOx emissions from HDTs from 2024 to 2027, the difference in NOx limits will be widened.

Figure B2.1 | **Limits on Nitrogen Oxide and Particulate Matter Emissions from Diesel Heavy-Duty Trucks in China, the European Union, and the United States**

Unit: grams/kilowatt-hour

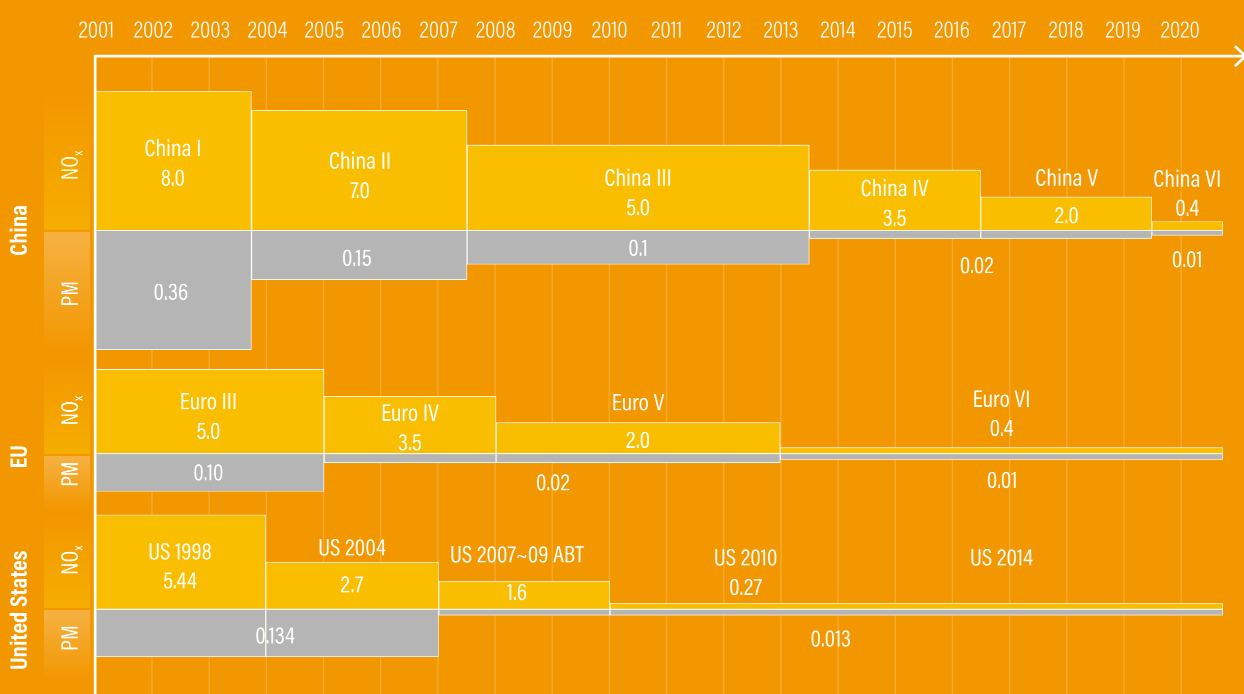


Figure source: Wei et al. 2020.

Box Notes: [a] ICCT 2017.

4.3 Attribution Analysis of Road Transport Decarbonization

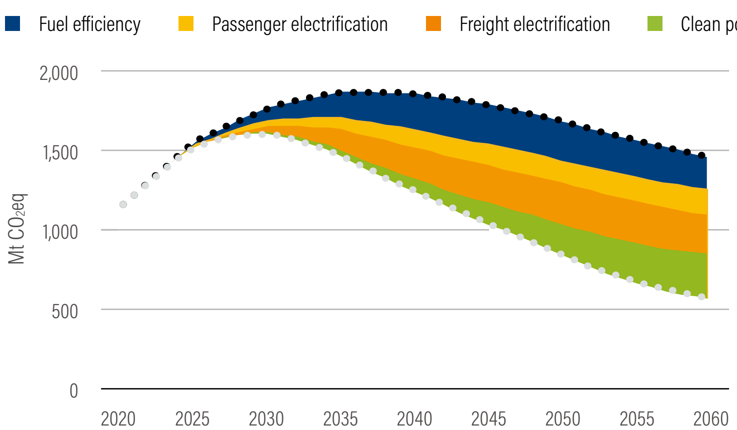
4.3.1 Decarbonization potentials of different measures

This section evaluates the decarbonization potentials of different measures and identifies what policies are needed to meet the 2060 carbon neutrality commitment.

Attribution analysis 1: From BAU to Stated_policy

The model results reveal that compared with the BAU scenario, stated policies would offer a 21,404 Mt CO_2eq cumulative emission reduction from 2020 to 2060. Among these policies, vehicle electrification measures offer the largest emission reduction (10,092 Mt CO_2eq), followed by improvements to vehicle fuel efficiency (7,003 Mt CO_2eq) and power (and hydrogen) sector decarbonization (4,309 Mt CO_2eq). Realizing these decarbonization potentials is contingent upon successfully implementing the stated policies (Figure 33 and Table 15).

Figure 33 | **Greenhouse Gas Reduction Potentials of Key Decarbonization Interventions: From the BAU to Stated_policy Scenarios**



	2020–60 Cumulative emission reduction (Mt CO_2eq)
Fuel efficiency	7,003
Passenger transport electrification	3,601
Road freight electrification	6,491
Clean power/H_2	4,309

Abbreviations: BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; Mt CO_2eq = million tonnes of carbon dioxide equivalent; H_2 = hydrogen.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Table 15 | **Key Targets in the Stated Policy Scenario**

	STRUCTURAL CHANGES	VEHICLE ELECTRIFICATION	FUEL EFFICIENCY IMPROVEMENTS	POWER AND HYDROGEN DECARBONIZATION
Passenger transport	*Targets:* 425 cars per 1,000 persons, 70% green transport mode share in 2060[a]	*Targets:* By 2035: NEVs represent 50% of passenger car sales[b] By 2060: NEVs represent 100% of passenger car sales[c]	*Targets:* By 2025: fleet-average fuel consumption for passenger cars of 4 L/100 km; hybrid vehicles represent 60% of passenger car sales[d] By 2035: hybrid vehicles represent 100% of passenger car sales[e] By 2025: NEV energy efficiency of 12 kWh/100 km[f]	*Targets:* By 2050: 92% non-fossil fuels in power mix[g]
Freight transport	*Targets:* 50% of road freight in domestic tkm; average load: 9.5 tonnes per vehicle-kilometer[h]	*Targets:* By 2030: NEV trucks represent 12% of truck sales[i] By 2050: NEVs represent 50% of HDT sales[j]	*Targets:* By 2035: 20% improvement in HDTs' fuel consumption[k] Continuous improvement in NEVs' energy efficiency	*Targets:* By 2050: 15% gray hydrogen in production mix[l]

Notes: a. Extrapolated by WRI authors based on NDRC (2021). b. China SAE 2020. c. Extrapolated by WRI authors. d. MIIT 2019, 2021; China SAE 2020. e. MIIT 2019, 2021; China SAE 2020. f. State Council 2020. g. ICCSD 2020. h. Extrapolated by WRI authors based on NDRC (2021). i. China SAE 2020. j. China SAE 2020. k. Extrapolated by WRI authors. l. China SAE 2020. m. CHA 2019.
Abbreviations: NEV = new energy vehicle; L = liter; km = kilometer; kWh = kilowatt-hour; tkm = tonne-kilometers; HDT = heavy-duty truck.

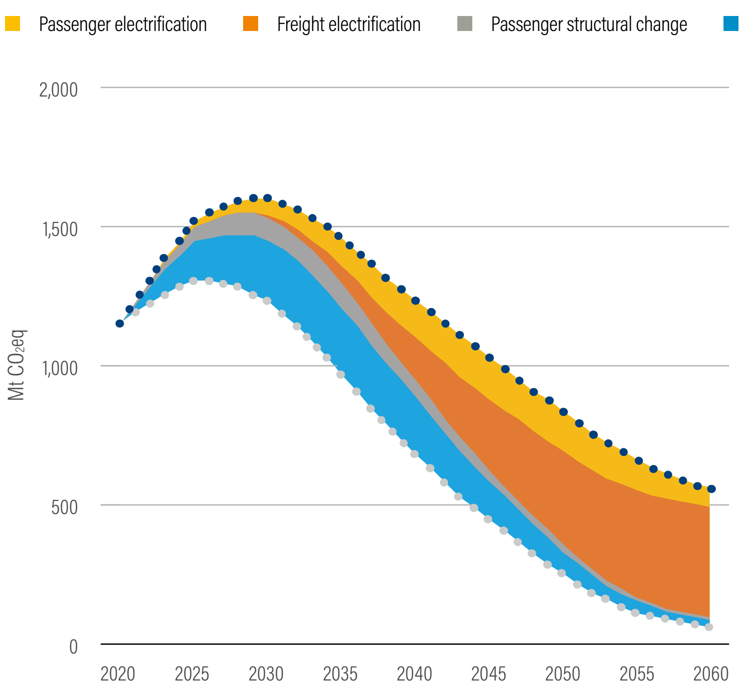
Attribution analysis 2: From Stated_policy to DeepDecarb

To further cut emissions from the level in the Stated_policy scenario to that in the DeepDecarb scenario, this study shows that China's road transport sector needs more ambitious targets on vehicle electrification and structural changes (see Figure 34 and Table 16). Compared with the Stated_policy scenario,

- higher vehicle electrification targets—including 100 percent NEVs in passenger car sales by 2035 and 100 percent NEVs in long-haul HDT sales and refrigerated HDT sales by 2050—would be instrumental to delivering an additional 11,007 Mt CO_2eq cumulative emission reduction; and
- explicit and radical structural change targets—including 40 percent of road freight in the total tkm and an average 11.5 tonne load per HDT vehicle-kilometer—would be key to delivering an additional 7,175 Mt CO_2eq cumulative emission reduction.

Altogether, decarbonizing the freight sector offers the largest emission reduction potential of 12,568 Mt CO_2eq.

Figure 34 | **Greenhouse Gas Reduction Potentials of Key Decarbonization Interventions: From Stated_policy to DeepDecarb Scenarios**



	2020–60 Cumulative emission reduction (Mt CO_2eq)
Passenger transport electrification	3,768
Road freight electrification	7,239
Passenger structural change	1,846
Freight structural change	5,329

Abbreviations: BAU = Business as Usual scenario; Stated_policy = Stated Policy scenario; Mt CO_2eq = million tonnes of carbon dioxide equivalent; H_2 = hydrogen.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Table 16 | **Key Targets and Policy Interventions to Achieve Deep Decarbonization**

	STRUCTURAL CHANGES	VEHICLE ELECTRIFICATION	FUEL EFFICIENCY IMPROVEMENTS	POWER AND HYDROGEN DECARBONIZATION
Passenger transport	***Targets:*** 300 cars per 1,000 persons, 75–85% green transport mode share in 2060	***Targets:*** NEVs represent 100% of passenger car sales in 2035	Same targets as the Stated_policy scenario	Same targets as the Stated_policy scenario
	Tactics: • Shift transit service paradigm with intelligent demand responsive services • Increase the share of infrastructure investments in transit, active mobility, and railway • Pursue travel demand management and carbon pricing • Promote Mobility-as-a-Service and ride sharing	***Tactics:*** • Enhance fleet-wide fuel consumption standard • Provide road access privileges to NEVs • Increase infrastructure accessibility • Introduce carbon taxes		
Freight transport	***Targets:*** 40% of road freight in domestic tkm; average load = 11.5 tonnes per HDT vehicle-kilometer	***Targets:*** NEVs represent 100% of HDT sales in 2050 (HDTs for short-range and long-range duty cycles)	Same targets as the Stated_policy scenario	Same targets as the Stated_policy scenario
	Tactics: • Shift bulk commodities to railways and waterways and promote intermodal freight for high-value freight • Invest in intermodal infrastructure and equipment, improve service connectivity, rationalize pricing and scheduling, and enhance first-/last-mile truck delivery • Encourage the use of non-truck operating carriers and facilitate drop-and-hook operations • Employ fuel taxes and road charges	***Tactics:*** • Increase vehicle acquisition and introduce operation subsidies • Introduce fleet-wide fuel consumption standard for HDTs • Introduce CO_2-emission indexed road pricing • Provide road access privileges • Increase infrastructure accessibility		

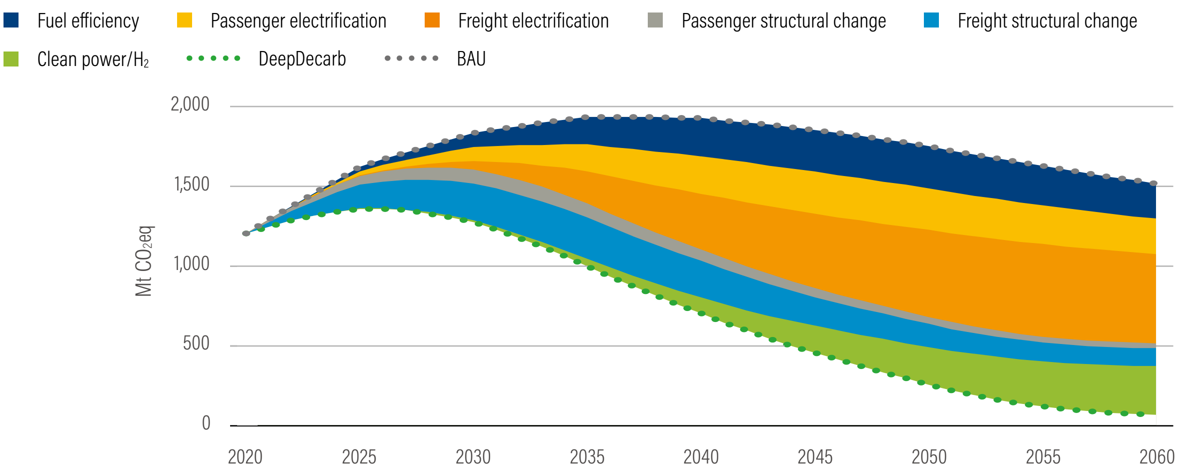
Abbreviations: NEV = new energy vehicle; tkm = tonne-kilometer; HDT = heavy-duty truck; CO_2 = carbon dioxide.
Source: WRI authors' recommendations.

Attribution analysis 3: From BAU to DeepDecarb

To bend the emission curve from that in the BAU scenario to that in the DeepDecarb scenario, three decarbonization measures must occur in the country's road transport sector (see Figure 35):

- Vehicle electrification—especially for heavy- and light-duty trucks—has the largest decarbonization potential over the long term, contributing to 48 percent of the cumulative GHG emission reduction from 2020 to 2060. If the carbon intensity of upstream power/hydrogen generation is reduced simultaneously, vehicle electrification could result in a 60 percent cumulative emission reduction.
- Structural changes and fuel efficiency improvements are the second- and third-most effective measures to be undertaken, respectively. Structural change measures have the second-largest mitigation potential over the long term—by managing vehicle fleet growth and kilometers travelled, cumulative GHG emissions from 2020 to 2060 could be cut by 23 percent. Energy efficiency improvements could generate a 17 percent cumulative emission reduction; tightening the fleet-wide fuel efficiency standard also has the benefit of stimulating NEV production (Wappelhorst et al. 2021).

Figure 35 | **GHG Reduction Potentials of Key Decarbonization Interventions: From Business as Usual to Deep Decarbonization**



	2020–35		2035–60	
	AVERAGE ANNUAL EMISSION REDUCTION (Mt CO_2eq/year)	CUMULATIVE EMISSION REDUCTION (Mt CO_2eq)	AVERAGE ANNUAL EMISSION REDUCTION (Mt CO_2eq/year)	CUMULATIVE EMISSION REDUCTION (Mt CO_2eq)
Fuel efficiency	65	1,036	240	6,003
Passenger transport electrification	61	982	239	5,970
Road freight electrification	51	821	468	11,703
Passenger structural change	62	996	52	1,302
Freight structural change	167	2,679	167	4,165
Clean power/H_2	12	187	196	4,899

Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; H_2 = hydrogen; BAU = Business as Usual scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

However, these instruments have varying mitigation potentials over time:

- In the near term (2020–35), structural changes have the largest mitigation potential because the adoption of NEVs will have not yet reached a tipping point.

- Over the long term (2035–60), the uptake of NEVs will overtake structural changes to have the largest mitigation potential. To unlock the long-term abatement potential of vehicle electrification, technology advances are necessary, particularly the development of zero-emission technologies on long-haul HDTs and refrigerated HDTs (currently, two to five times more expensive than ICE HDTs) as well as low-cost technologies for green hydrogen production and distribution (currently, three to four times more expensive than gray hydrogen) (IRENA 2020).

From a sectoral perspective, freight transport would play a more important role than passenger transport. Concretely, attaining the carbon neutrality goal requires a radical shift in truck fleet technologies and freight structures:

- Truck electrification (both light- and heavy-duty trucks) would need to result in a reduction of 12,524 Mt of cumulative emissions—nearly two times the emission reduction associated with passenger vehicle electrification. Particularly, technologies and policies need to tackle the hard-to-abate long-haul HDTs and refrigerated HDTs.

- Freight transport's structural changes would need to result in a reduction of 6,844 Mt of cumulative GHG emissions—nearly three times the emission reduction associated with passenger transport's structural changes. Particularly, explicit freight structural change targets and coordinated policies are needed to facilitate the transition.

Further, to inform decarbonization policymaking in the freight sector, China needs better statistical data systems on commodity flows (by mode, distance, and origin/destination pairs) as well as HDT fleet breakdowns by operational duty cycles.

Attribution analysis 4: Decarbonization potential of NG vehicles

NG vehicles account for a considerable fraction of China's vehicle fleet. This study assumes that the CH_4 TTW emission factor for China 5 heavy-duty trucks is 3 percent of NG consumption, and the emission factor for China 6 heavy-duty trucks ranges from 0.4 to 1 percent of NG consumption based on on-road testing results (Pan et al. 2020). The estimated per-vehicle emissions show that the CO_2 emissions from an LNG heavy-duty vehicle are 20 percent lower than those from a diesel vehicle, but the GHG emission reduction potential of an LNG heavy-duty vehicle is less significant:

- For China 6 LNG heavy-duty vehicles, the TTW GHG emissions (20-year GWP) are 12 percent lower than those from a diesel vehicle when the TTW CH_4 emission factor is 0.4 percent of NG consumption, and the GHG emissions are about the same as those of diesel vehicles when the TTW CH_4 emission factor is 1 percent.

- For China 5 LNG heavy-duty vehicles, the TTW GHG emissions are even higher than those from diesel vehicles as larger amounts of methane escape from China 5 vehicles (such as crankcase emissions and dynamic venting of the fuel system) that outweigh the CO_2 emissions savings (Pan et al. 2020; Mottschall et al. 2020).

To evaluate the GHG emission implications of the expected promotion of NG vehicles, we compared the Stated_policy scenario with an NG scenario (see Figure 36). In the NG scenario, LNG heavy-duty trucks meeting the China 6 emission standard represent 20 percent of the annual heavy-duty truck sales in 2030 (higher than the 15 percent in the Stated_policy scenario), and 50 percent in 2050 (compared with the constant 15 percent in the Stated_policy scenario). The results show the following (see Figure 37):

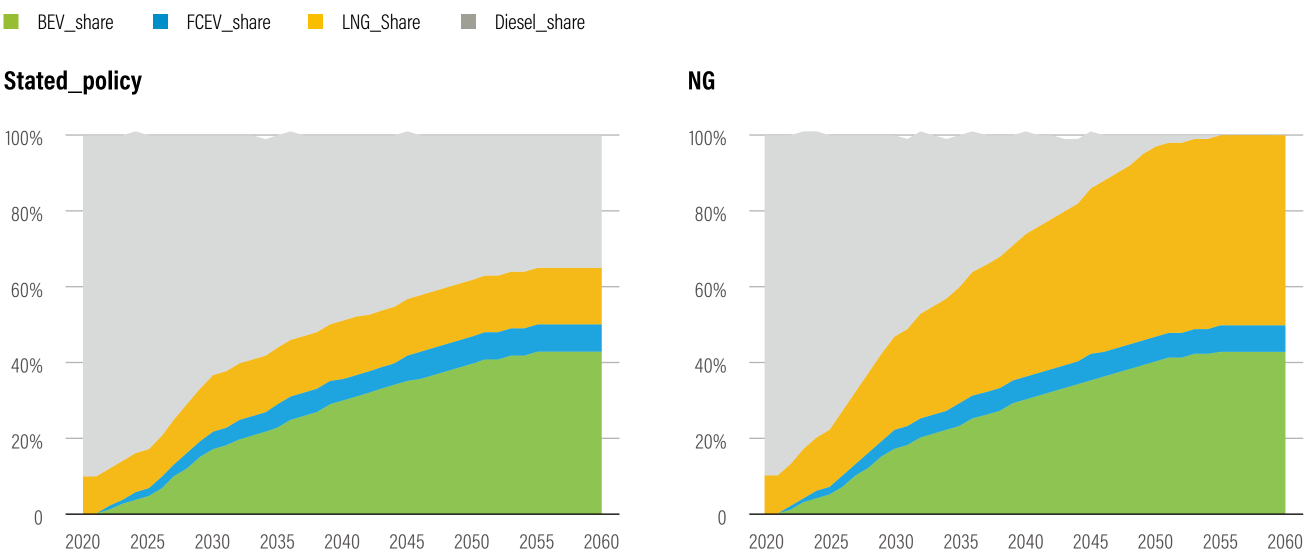
- In 2060, a larger NG fleet in the NG scenario would result in an 11 percent further reduction in CO_2 emissions and a less than 7 percent further reduction in GHG emissions compared with the Stated_policy scenario.

- For cumulative emissions reductions from 2020 to 2060, a larger fleet of LNG heavy-duty trucks in the NG scenario would lead to a 3 percent cumulative CO_2 emission reduction compared with the Stated_policy scenario; the cumulative GHG emission reduction would be even lower, at less than 3 percent.

In summary, the above analysis indicates that when the China 6 standard is stringently enforced and the real-world emissions of NG vehicles meet (or are lower than) the CH_4 emission limit, an LNG heavy-duty truck would result in an up to 20 percent CO_2 emission reduction and 12 percent GHG emission reduction compared with the emissions from a diesel truck. In the scenario analysis, when the market share of LNG heavy-duty trucks rises to 50 percent in 2050 in the Stated_policy scenario (compared with the original 15 percent), the wider adoption of LNG trucks leads to 7 percent GHG emission reduction in 2060 and to a less than 3 percent cumulative GHG emission reduction from 2020 to 2060 compared with the Stated_policy scenario. If the upstream WTT emissions associated with NG processing are taken into account, the GHG emission reduction potential of NG vehicles would possibly further shrink (Pan et al. 2020).

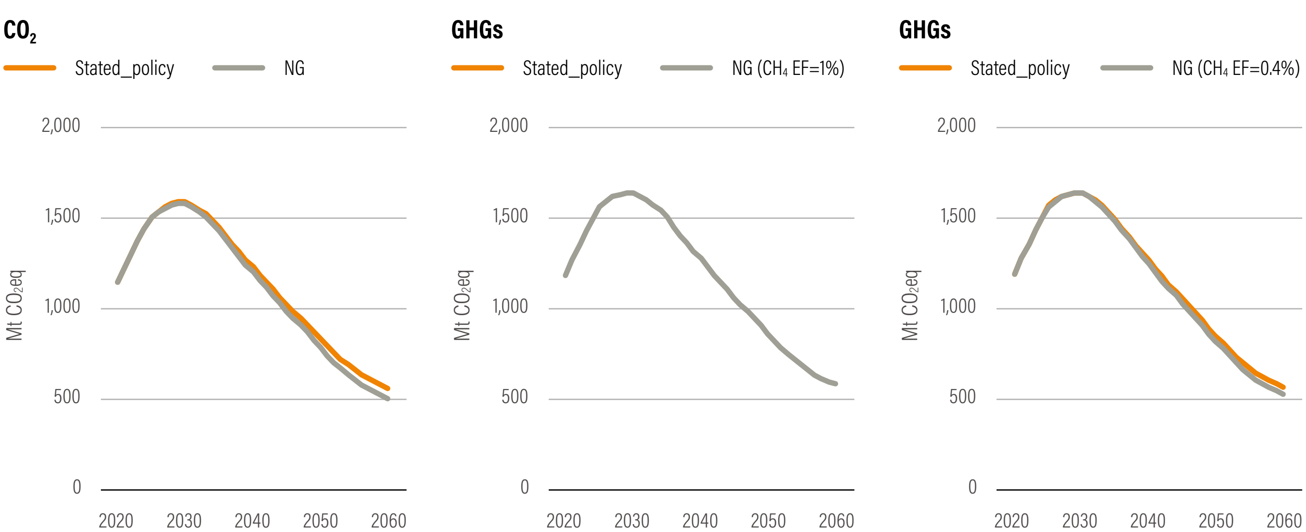
Apart from the limited environmental benefit, the widespread uptake of NG vehicles also raises concerns over NG import dependency, NG price affordability, and newly added NG infrastructure such as pipelines and storage reservoirs that could soon become stranded assets when NEVs take hold. Therefore, China needs to scrutinize its 2030 clean energy vehicle target (40 percent) in the *Action Plan* to determine whether and to what extent NG vehicles should be promoted.

Figure 36 | **Annual Sales in the Stated_policy and Natural Gas Scenarios**



Abbreviations: NG = natural gas; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; LNG = liquefied natural gas.
Source: WRI authors' assumptions.

Figure 37 | **Comparison of Carbon Dioxide and Greenhouse Gas Emissions in the Stated_policy and Natural Gas Scenarios**



Notes: The methane tank-to-wheel emission factor for China 5 heavy-duty trucks is 3 percent of NG consumption, and the emission factor for China 6 heavy-duty trucks ranges from 0.4–1 percent of NG consumption depending on on-road testing results (Pan et al. 2020). Methane uses 20-year global warming potential values from IPCC (2014).
Abbreviations: Mt CO_2eq = million tonnes of carbon dioxide equivalent; GHGs = greenhouse gases; NG = natural gas; CH_4 = methane; EF = emission factor.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

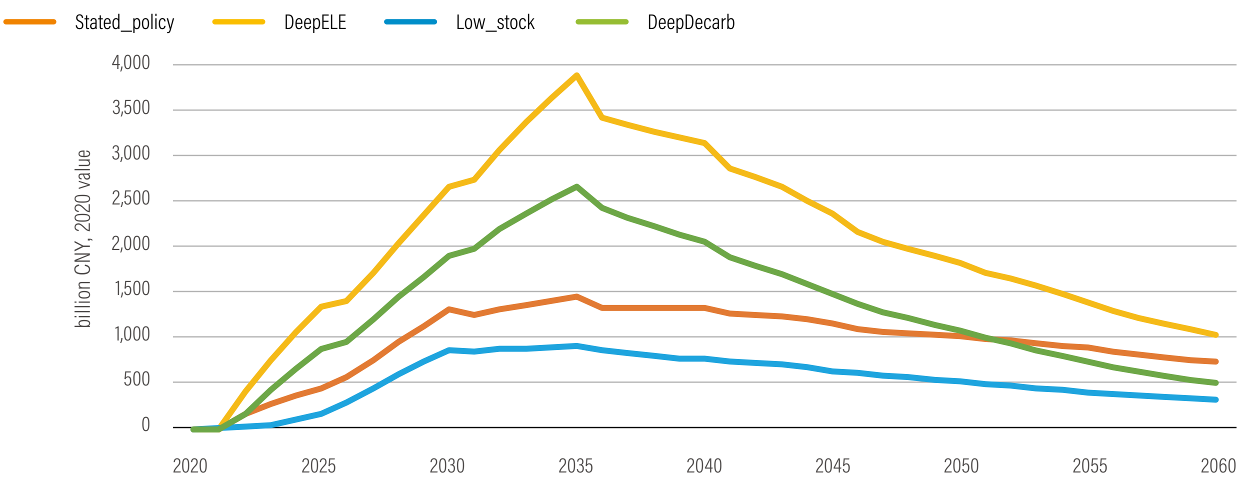
4.3.2 Marginal abatement cost analysis

Decarbonizing the transport sector requires making large investments in both traditional and emerging fields—from making railway and street improvements to acquiring NEVs and expanding the charging/refueling network. Studies suggest that to enable China's net-zero transition, 90–174 trillion CNY in cumulative low-carbon investments will need to be mobilized from 2020 to 2050 (BCG 2020; ICCSD 2020; Goldman Sachs 2021). Across all sectors, the transport sector will attract the most investment according to BCG (2020), or the second most—following the power sector—according to ICCSD (2020).

This study first evaluates the levels of low-carbon investment required to achieve the GHG emissions reduction in the different scenarios compared with those in the BAU scenario, using the method outlined in Section 2.2.2. Two types of low-carbon investments are considered, namely NEV promotion and infrastructure investments to facilitate structural changes.

The results show that large low-carbon investments amounting to 39–83 trillion CNY cumulatively are needed from 2020 to 2060 (compared with the BAU scenario) to decarbonize China's road transport sector. The levels of investment are greater than those found in BCG (2020), ICCSD (2020), and Goldman Sachs (2021) because we used a longer time frame and broader coverage of investments (Figure 38).[xvi] The investment demand is the largest from now till 2035 and will steadily decline over time. Among all the scenarios, the Low_stock scenario provides the lowest-cost mitigation pathway due to a smaller vehicle fleet (the average abatement cost is 675 CNY per tonne of CO_2eq reduced). The DeepELE scenario is the highest-cost mitigation pathway, with an average abatement cost of about three times (2,510 CNY per tonne CO_2eq reduced) the cost in the Low_stock scenario.

Figure 38 | **Low-Carbon Investments (2020-60) under Different Scenarios**



	Stated_policy	DeepELE	Low_stock	DeepDecarb
Cumulative low-carbon investments (billion CNY, 2020 value)	39,503	83,896	22,070	54,226
Average abatement cost (CNY per tonne CO_2eq reduced)	1,852	2,510	675	1,331

Abbreviations: CNY = Chinese yuan; CO_2eq = carbon dioxide equivalent, Stated_policy = Stated Policy scenario; DeepELE = Deep Electrification scenario; Low-stock = Structural Change scenario; DeepDecarb = Deep Decarbonization scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

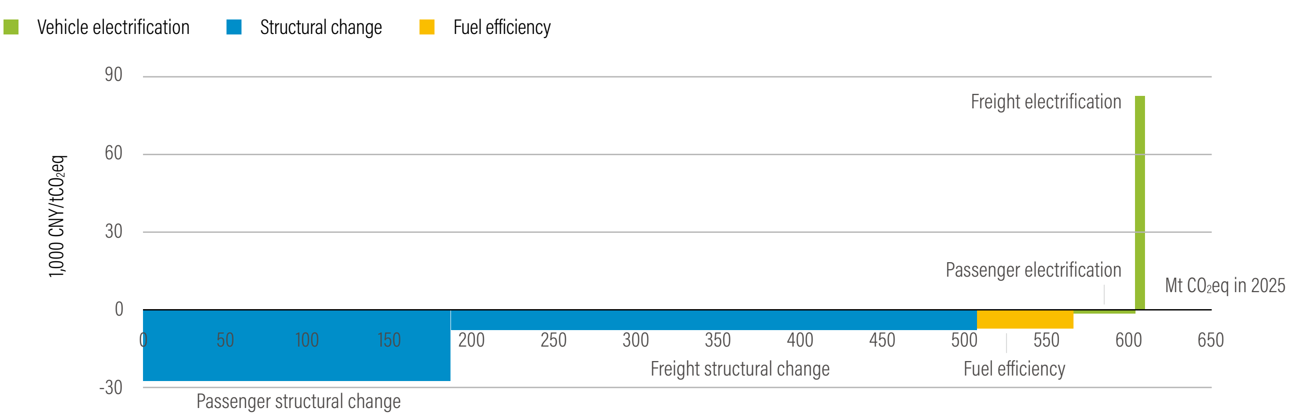
Further, we constructed marginal abatement cost curves (MACCs) to evaluate the cost-effectiveness of the mitigation measures in the DeepDecarb scenario in comparison to the BAU scenario. As the abatement costs evolve rapidly over time, we chose to look at three snapshots—2025 (that is, the 14th five-year period), 2030, and 2050 (see Figures 39, 40, and 41, respectively). The three MACCs indicate the following:

- Structural changes and fuel efficiency improvements are consistently low-cost options. Compared with the BAU scenario, both measures offer considerable net cost savings. For example, although public transit and freight infrastructure are expensive, structural changes can lead to considerable cost savings for vehicle acquisition, operation, and charging/hydrogen infrastructure installation, owing to a smaller vehicle fleet. Consequently, the unit abatement costs of passenger and freight structural changes in 2030 are -14.7 CNY and -4.1 CNY per kilogram of GHG reduced, respectively (Figure 40). Making fuel efficiency improvements is another cost-saving option, with a unit abatement cost of -4.0 CNY per kilogram in 2030. This is because cost-efficient ICE technologies to reduce fuel consumption (such as hybridization, new engine technologies, and vehicle downsizing) will have yet to be deployed at scale. The future fuel savings from ICE vehicles would be large enough to offset the rise in vehicle prices (to meet stricter fuel consumption standards) (Yang and Cui 2020).
- Abatement costs change significantly for vehicle electrification. For example, the unit abatement cost of freight vehicle electrification declines from 81.9 CNY per kilogram in 2025 to 5.8 CNY in 2030 and -0.6 CNY in 2050 (Figures 39, 40, and 41, respectively). This is because from now until 2030, the lifetime TCO of NEV HDTs will remain high. Only after TCO parity is reached around 2030–35 will NEVs become an affordable option, exhibiting net cost savings compared with ICE vehicles.

The following is noteworthy:

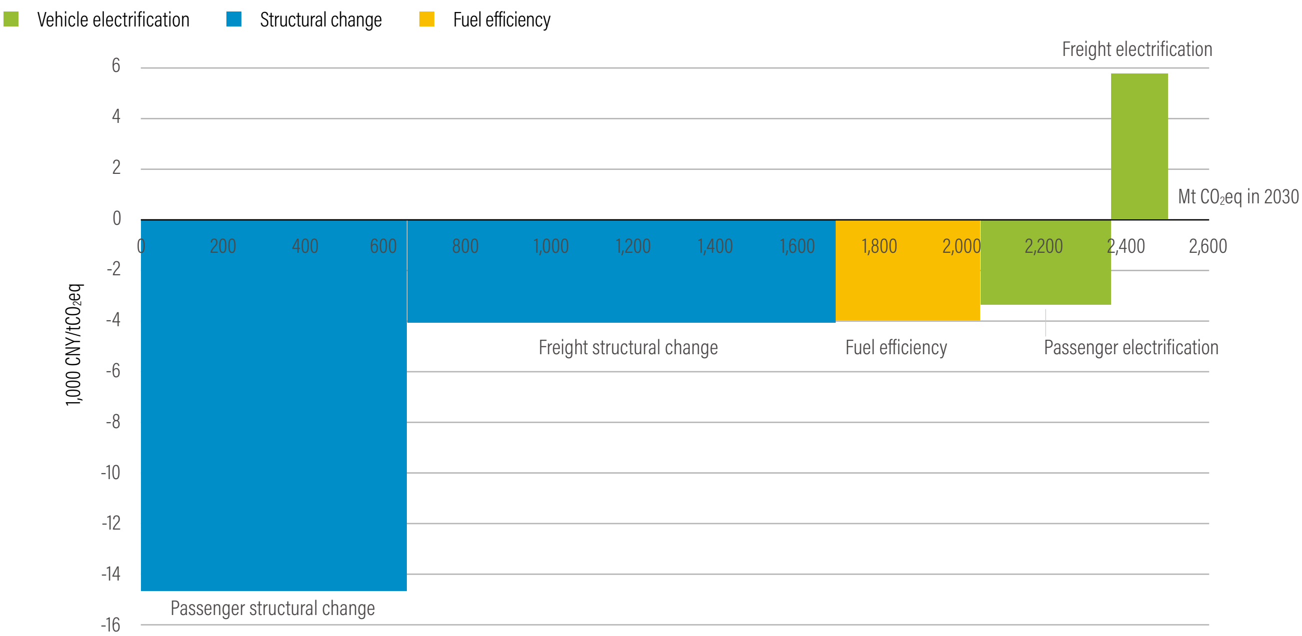
- Although needed investments in public transit and freight railways are lower, investments alone do not lead to mode shift. Without complementary measures, solely making infrastructure investments would have the associated risk of leading to infrastructure underutilization, which would result in higher emissions than having highly utilized infrastructure (Spielmann et al. 2010; ITF 2013). Therefore, comprehensive instruments such as travel demand management, MaaS, emission-based road pricing, and service quality improvements should be employed.
- The high abatement costs of vehicle electrification should not deter relevant investments. In fact, investments in vehicle acquisition and infrastructure expansion are critical because only through economies of scale (as NEVs become more widely adopted) would NEV costs drop.

Figure 39 | **Annual Marginal Abatement Cost Curve for 2025**



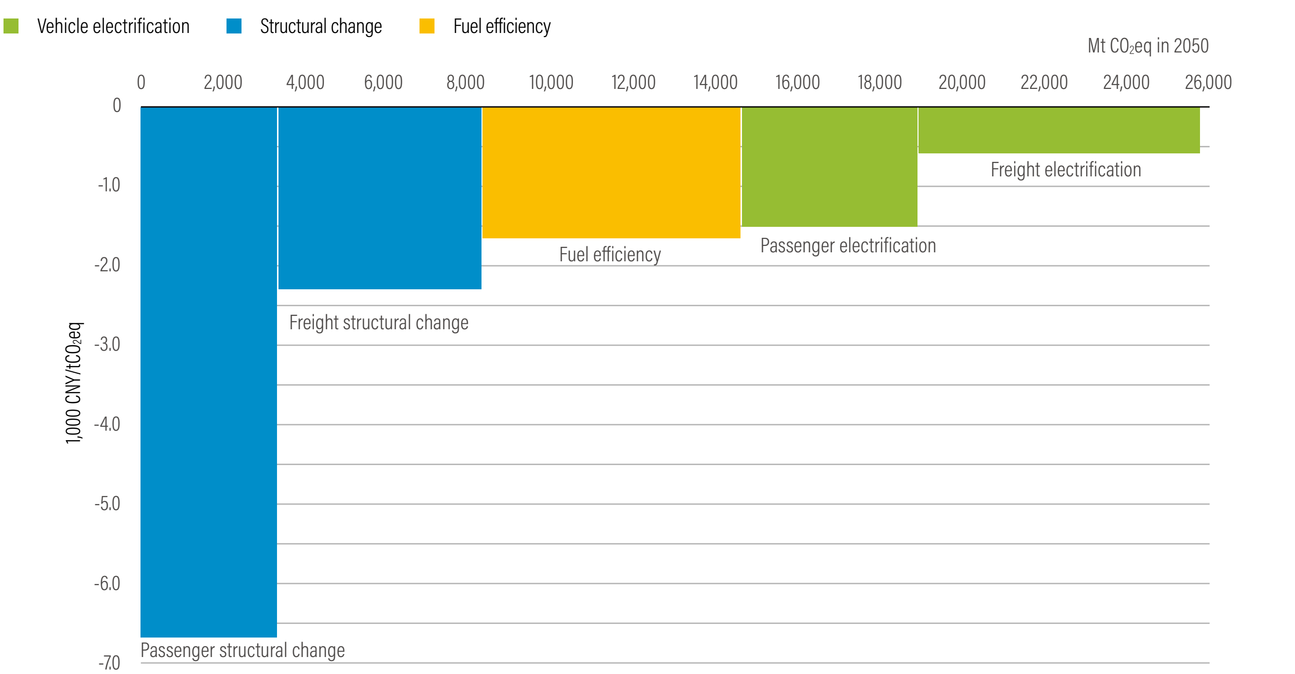
Abbreviations: CNY = Chinese yuan; tCO_2eq = tonnes of carbon dioxide equivalent; Mt = million tonnes.
Source: WRI authors' calculations.

Figure 40 | **Annual Marginal Abatement Cost Curve for 2030**



Abbreviations: CNY = Chinese yuan; tCO_2eq = tonnes of carbon dioxide equivalent; Mt = million tonnes.
Source: WRI authors' calculations.

Figure 41 | **Annual Marginal Abatement Cost Curve for 2050**



Abbreviations: CNY = Chinese yuan; tCO_2eq = tonnes of carbon dioxide equivalent; Mt = million tonnes.
Source: WRI authors' calculations.

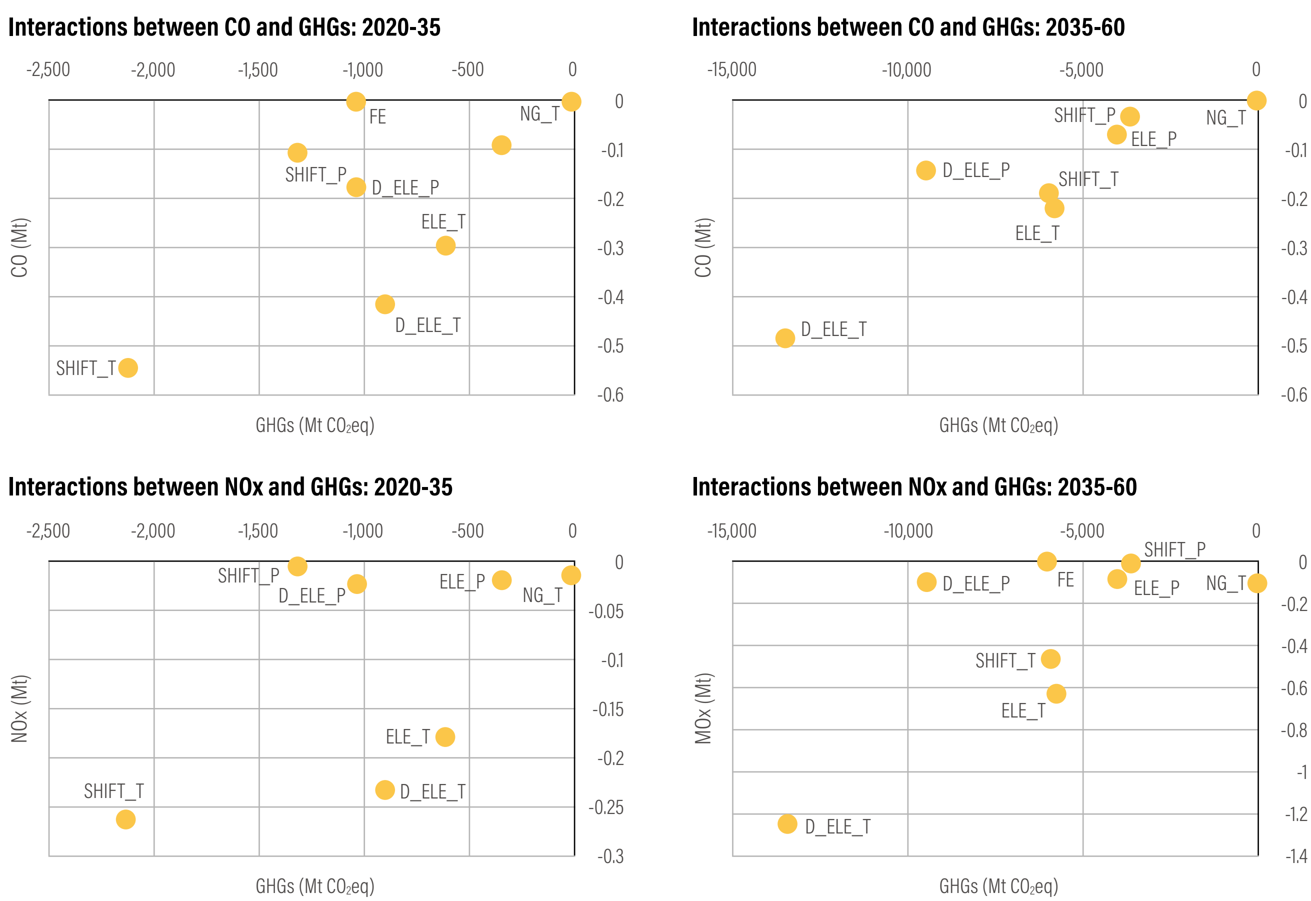
4.4 GHG Emissions and Air Pollutant Co-control Potentials

Measures with large decarbonization potentials at low cost do not necessarily produce air quality co-benefits.

To evaluate mitigation measures' co-control potentials in reducing GHGs and air pollutants, we employed a "co-control effect coordinate system" (Hu et al. 2020). In the coordination system (see Figure 42), the vertical axis and the horizontal axis, respectively, represent the cumulative GHG emission reduction and cumulative air pollutant reduction compared with the BAU scenario. Mitigation measures falling in the third quadrant are the measures with co-control potential. We investigated cumulative emission reductions under two time frames—the near term (2020–35) and the long term (2035–60).

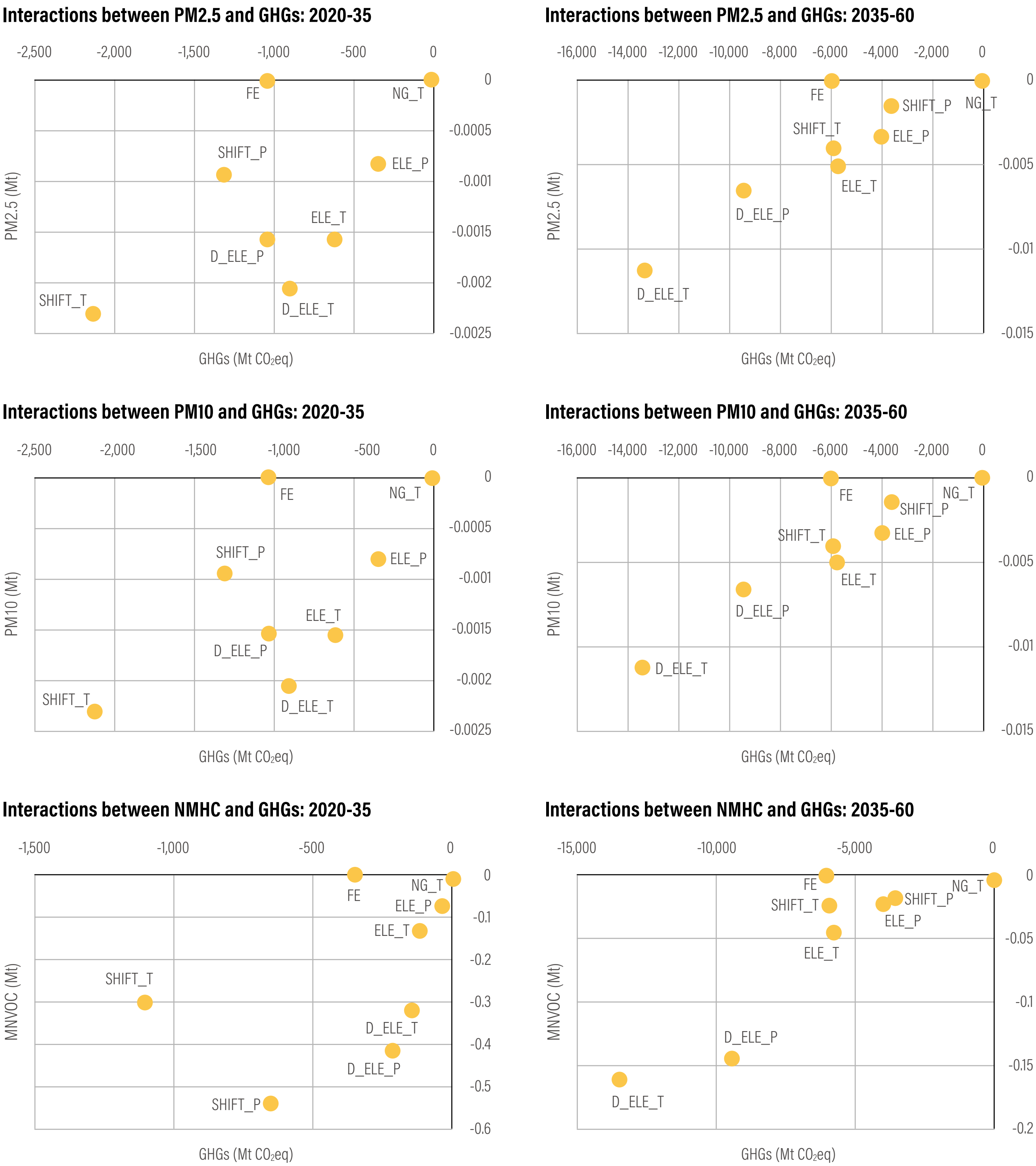
As shown in Figure 42, vehicle electrification and structural changes not only have the largest decarbonization potentials, but also the greatest potential to curb air pollution. However, not all GHG mitigation measures would deliver air quality co-benefits (Table 17):

Figure 42 | **Co-control Potentials of Different Decarbonization Measures Compared with the Business as Usual Scenario**



Note: Abbreviations: CO = carbon monoxide; GHG = greenhouse gas; NOx = nitrogen oxides; PM2.5 = particular matter less than 2.5 micrometers in diameter; PM10 = particular matter less than 10 micrometers in diameter; NMHC = non-methane hydrocarbons; Mt CO_2eq = million tonnes of carbon dioxide equivalent; D_ELE_T = freight vehicle electrification in the DeepELE scenario; D_ELE_P = passenger vehicle electrification in the DeepELE scenario; ELE_T = freight vehicle electrification in the Stated_policy sceniario; ELE_T = passenger vehicle electrification in the Stated_policy scenario; FE = fuel efficiency improvement in the Stated_policy scenario; SHIFT_T = freight structural change in the Low_stock scenario; SHIFT_P = passenger structural change in the Low_stock scenario; NG_T = natural gas vehicle adoption in the Stated_policy scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Figure 42 | **Co-control Potentials of Different Decarbonization Measures Compared with the Business as Usual Scenario**



Abbreviations: CO = carbon monoxide; GHG = greenhouse gas; NOx = nitrogen oxides; PM2.5 = particular matter less than 2.5 micrometers in diameter; PM10 = particular matter less than 10 micrometers in diameter; NMHC = non-methane hydrocarbons; Mt CO_2eq = million tonnes of carbon dioxide equivalent; D_ELE_T = freight vehicle electrification in the DeepELE scenario; D_ELE_P = passenger vehicle electrification in the DeepELE scenario; ELE_T = freight vehicle electrification in the Stated_policy sceniario; ELE_T = passenger vehicle electrification in the Stated_policy scenario; FE = fuel efficiency improvement in the Stated_policy scenario; SHIFT_T = freight structural change in the Low_stock scenario; SHIFT_P = passenger structural change in the Low_stock scenario; NG_T = natural gas vehicle adoption in the Stated_policy scenario.
Source: WRI authors' calculations using the Low Emissions Analysis Platform model.

Table 17 | **The Co-control Effects of Different Decarbonization Measures**

	RESEARCH	CO-CONTROL EFFECTS	POLICY IMPLICATIONS
Fuel efficiency standards	This study	● **General fuel efficiency measures:** Reduce GHG emissions, neutral to air pollutants	--
	O'Driscoll et al. 2018	● **Hybrid (gasoline) vehicles:** Reduce GHG and air pollutants	Promote hybrid (gasoline) vehicles
	Liang et al. 2012 Saliba et al. 2017 O'Driscoll et al. 2018	● **Gasoline direct injection:** Reduce GHG emissions but increase air pollutants	Enforce China 6 standard and enhance inspection/ maintenance programs for in-use vehicles
NG vehicle promotion	This study Mottschall et al. 2020 T&E 2020a	● **NG vehicles:** Possibly increase GHG emissions, reduce/ neutral to air pollutants	Tighten China 6 standard on non-tailpipe CH_4 emissions from NG vehicles, enhance inspection/ maintenance programs
NEV promotion	This study	● **NEV promotion:** Reduce GHG emissions and air pollutants	--
	Peng et al. 2021	● **NEVs and upstream emissions:** Reduce GHG emissions, increase upstream air pollutants	Couple NEV promotion with the decarbonization of the upstream power and industrial sector
Passenger structural changes	This study	● **Passenger structural changes:** Reduce GHG emissions and air pollutants	--
Freight structural changes	This study	● **Freight structural changes:** Reduce GHG emissions and air pollutants	--
	Shao 2020	● **Freight structural changes (mode shift to railways):** Reduce GHG emissions, increase upstream air pollutants	Decarbonize the upstream power sector, promote railway electrification, and reduce railway backhauls

Notes: Green cells ● indicate that the measure can reduce both GHG emissions and air pollutants, and yellow cells ● mean that the measure can reduce only GHG/ air pollutant emissions.
Abbreviations: GHG = greenhouse gas; CH_4 = methane; NG = natural gas; NEV = new energy vehicle.
Source: WRI authors, based on this study and existing literature.

- Limited co-control effects were found for fuel efficiency improvement measures—fuel efficiency improvements lead to GHG emission reductions but are neutral to air pollution control. In fact, in the real world, different energy-efficiency technologies lead to varying co-control effects. For example, hybrid (gasoline) vehicle technologies emit less GHG emissions and air pollutants, especially in urban driving conditions (O'Driscoll et al. 2018). By contrast, gasoline direct injection (GDI) engine technology as an emerging fuel-efficiency measure (Saliba et al. 2017; O'Driscoll et al. 2018) generates more particulate masses and numbers than traditional technologies (Liang et al. 2012; O'Driscoll et al. 2018). Although remedy measures such as gasoline particulate filters help mitigate GDI vehicles' particulate emissions (Saliba et al. 2017), they tend to lead to fuel economy penalties and CO_2 emission increases (Mamakos 2011).[xvii]

- For tailpipe emissions, NEV promotion and structural changes have co-control potential. Nonetheless, for WTW emissions, some studies suggest NEV promotion would increase GHG emissions and air pollutants when electricity generation uses the 2015 power mix and hydrogen is produced from coal gasification and steam methane reforming (Peng et al. 2021). Likewise, due to coal-dependent electricity generation and the use of diesel trains and empty backhauls of railway shipments, freight mode shift from road transport to electric trains tends to emit more GHGs, PM, and NOx (Shao 2020). Therefore, for NEV promotion and freight mode shift to yield air quality and climate co-benefits, the measures must be coupled with decarbonization of the upstream power and industrial sectors as well as railway electrification and improvements in operational efficiency.


citi
人民路
Renmin Rd.
入

CHAPTER 5

CONCLUSION AND DISCUSSION

Although this study examines how China's road transport sector might be decarbonized, it also has limitations such as the unidimensional goal of GHG emission mitigation, the lack of causal links between interventions and policy targets, and the underestimation of certain emissions.

China's road transport sector plays an important role in meeting carbon early peaking and carbon neutrality goals. This study examines how the sector might be decarbonized by modelling five scenarios using the LEAP model. The results indicate the following:

First, in the medium term, the peaking timeline for GHG emissions from China's road transport sector would be during 2025–35 and that for petroleum demand would be during 2024–30 under all scenarios except Business as Usual. If the country's stated policies are effectively implemented over time, China could peak road transport emissions before 2030 and petroleum consumption before 2027. The peaking timeline could be further advanced to 2025 for GHG emissions and 2024 for petroleum consumption by employing structural change measures.

Second, over the long term, with policy interventions, it would be possible to reduce road transport GHG emissions in 2060 by 50–95 percent from 2020's level. To achieve the largest emission reduction potential of 95 percent, vehicle electrification, structural changes, fuel efficiency improvements, and power and hydrogen decarbonization are critical.

This study has the following limitations:

- First, we designed the scenarios to meet the unidimensional goal of GHG emission mitigation, which may not ensure that other sustainable development goals will also be met. For example, to alleviate traffic congestion, promote social equity, reduce road safety risks, and lessen public expenditure, more proactive structural change measures would be required.

- Second, the causal links between policy interventions (such as public subsidies and road pricing) and the attainment of policy targets (such as vehicle electrification and structural changes) are weak. Future quantitative analysis is necessary to strengthen the causal links and inform better policymaking.

- Third, air pollutants from motor vehicles vary significantly depending on the extent of aftertreatment device degradation, driving cycles, vehicle loads, weather conditions, and more. Without taking these factors into consideration, this study may overstate the effectiveness of the China 6 emission standard.

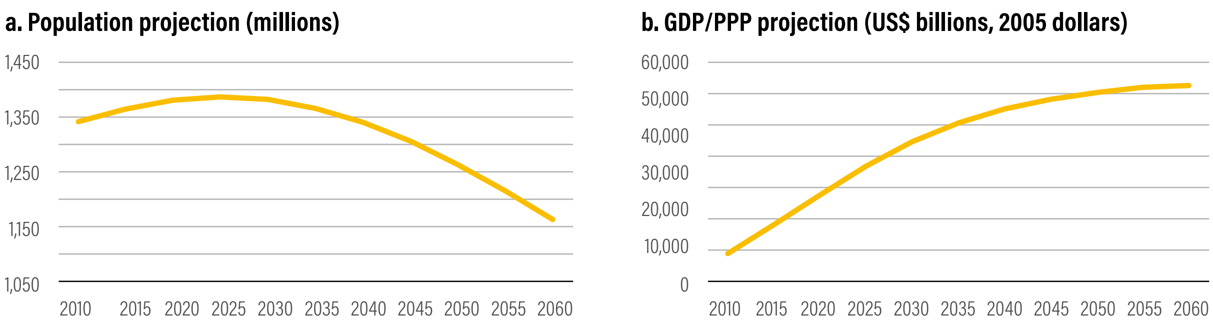
Over the long term, with policy interventions, it would be possible to reduce road transport GHG emissions in 2060 by 50–95 percent from 2020's level.


重庆长途汽车站

APPENDIX A. SOCIOECONOMIC ASSUMPTIONS AND DEMAND FORECASTING METHODS

The socioeconomic assumptions of this study are based on the Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2012), which are a set of socioeconomic projections (including for population and GDP) widely adopted by the integrated assessment model community. Among six SSP pathways, SSP2 was adopted for this analysis because it is designed to extend historical trends. In the SSP2 pathway (Figure A1), China's population is forecast to peak

Figure A1 | **Population and GDP Projections in the Shared Socioeconomic Pathway 2**



	POPULATION PEAK YEAR	PEAK POPULATION	POPULATION IN 2060	GDP PEAK YEAR	GDP AS OF 2060
SSP2	2025–30	1.39 billion	1.16 billion	Not yet for 2060	US$52,145 billion (2005 dollars)

Abbreviations: SSP2 = Shared Socioeconomic Pathway 2; GDP = gross domestic product; PPP = purchasing power parity.
Source: WRI authors' calculations.

around 2025–30 at 1.39 billion. The GDP projection follows China's "New Normal," and per capita GDP is expected to increase to US$44,806 (in 2005 constant dollars) in 2060, almost seven times the 2010 level.

Passenger car ownership forecasting method

We used the Gompertz model (Equation 8) to model the long-term relationship between passenger car stocks and GDP per capita and to forecast China's future passenger car ownership.

$$V(x)=\gamma e^{\alpha e^{\beta x}} \quad \text{(Equation 8)}$$

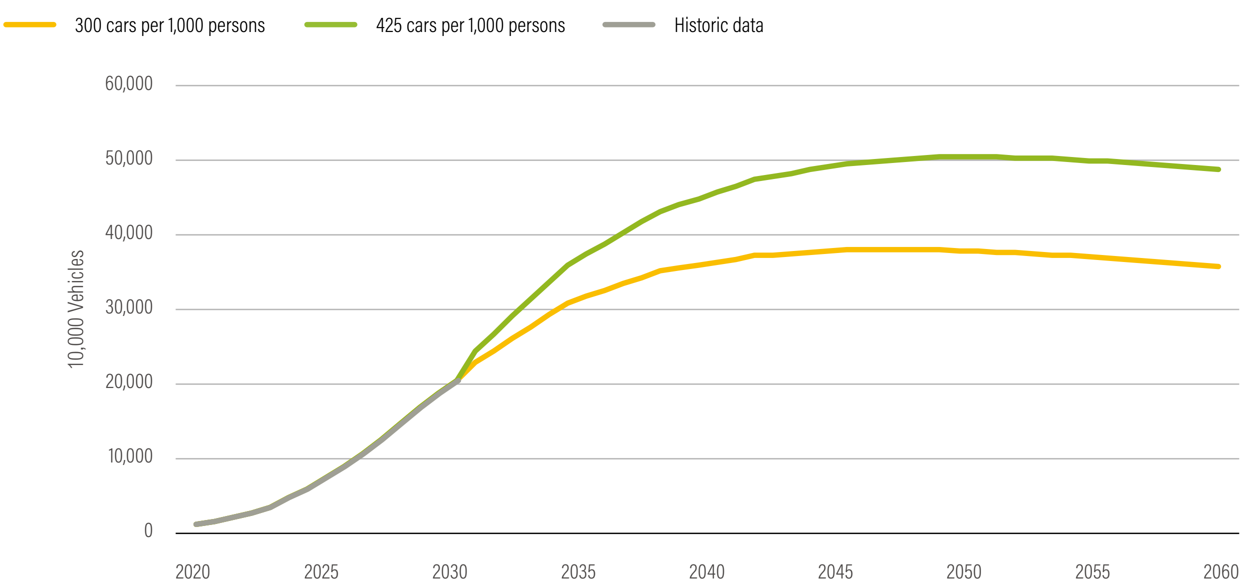
where,
$V(x)$ is the estimated vehicles per 1,000 persons
x is GDP per capita
γ is the future vehicle saturation level
α and β are the coefficients to be estimated using the equation

Equation 8 is transformed into Equation 9, which can be solved by linear regression:

$$ln(ln(V(x)\text{-}ln\gamma)=ln(\alpha)+ \beta x \quad \text{(Equation 9)}$$

We estimated the Gompertz curve using historical data on China's GDP per capita and vehicles per 1,000 persons (NBS 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019) as well as the assumed future car saturation levels. Based on the literature reviewed in Section 3.2.1, this study assumes that the saturation levels for car ownership would be 300 cars per 1,000 persons in the BAU scenario and 425 cars per 1,000 persons in the Structural Change scenario in 2060. The empirical results are shown in Figure A2. The results are statistically significant and indicate that China's car ownership is situated in the rapid growth stage and future maximum car ownership could range from 381 to 506 million.

Figure A2 | **China's Passenger Car Ownership Projection (2020-60) under Different Car Saturation Levels**



	LN(α)	β	MAXIMUM CAR OWNERSHIP
300 cars per 1,000 persons	-2.03060*** (-147)	-0.00015*** (-109)	381 million (2040)
425 cars per 1,000 persons	-1.98078*** (-195)	-0.00012*** (-122)	506 million (2045)

Notes: T-statistics are shown in parentheses: * p < 0.05; ** p < 0.01; *** p < 0.001.
Source: WRI authors' calculations.

Domestic freight tkm forecasting method

We employed the elasticity method that is commonly used in integrated assessment models to model the long-term nonlinear relationship among freight tkm, GDP per capita, and fuel (carbon) prices.

$$D(x)=\alpha\cdot x_{income}^{\beta}\cdot x_{price}^{\gamma} \qquad \text{(Equation 10)}$$

where,

D(x) is the estimated freight demand

x_{income}^{β} and x_{price}^{γ} are the indexes for income per capita and fuel (carbon) prices compared with the starting year (1990)

α is the starting year's calibrated coefficient

β and γ are the long-term income elasticity and price elasticity, respectively, to be estimated using the equation

Based on historical observations (1990–2020), we estimated China's long-term income elasticity for freight tkm. The result shows that the elasticity is higher than that in the United States (from 1980 to 2018) but slightly lower than that in Germany (from 1990 to 2020) (see Table A1). Using Germany as a benchmark, this study assumes China's income elasticity will remain fixed at 0.99.

For price elasticity, this study assumes the effect of fuel prices on freight demand was limited in the past but will become significant in the future. Using existing modelled elasticities in Edelenbosch et al. (2017), the study assumes China's long-term price elasticity will vary from -0.2 to -0.5 between 2020 and 2030, and from -0.5 to -0.7 between 2030 and 2060.

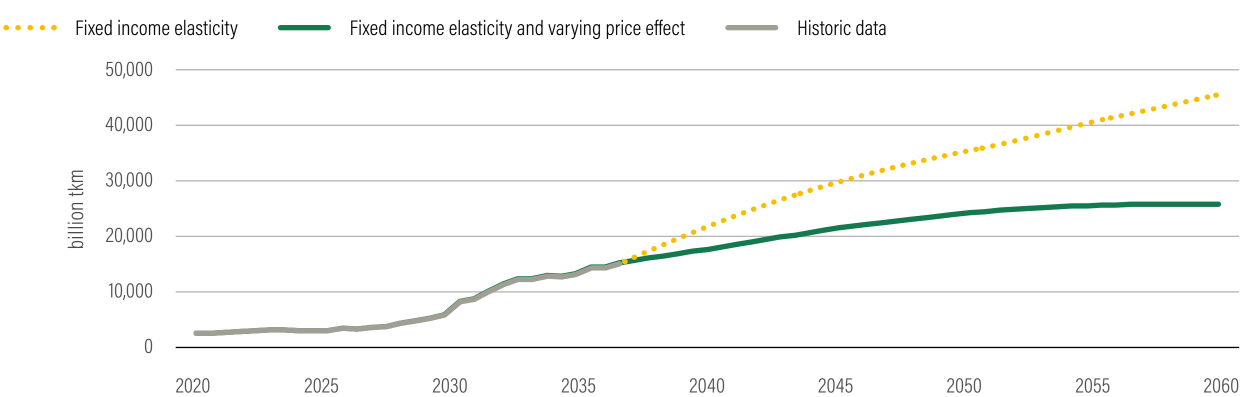
The projected result shows that China's freight demand is situated at the rapid growth stage and that future freight demand will plateau at 25.9 trillion tkm in 2055–60.

Table A1 | Long-Term Income Elasticities for Freight Demand in China, the United States, and Germany

CHINA (1990–2020)	UNITED STATES (1980–2018)	Germany (1990–2020)
0.99	0.40	1.01

Source: Freight demand data are from NBS (2021); BTS (2021a); and OECD (n.d.). Population and GDP data come from the World Bank database: https://data.worldbank.org.

Figure A3 | China's Domestic Freight Demand Forecast



	2020–30	2030–60
Income elasticity	0.99	0.99
Fuel (carbon) price elasticity	-0.2–-0.5	-0.5–-0.7

Abbreviation: tkm = tonne-kilometer.
Source: WRI authors' calculations.

APPENDIX B. LIFETIME TOTAL COST OF OWNERSHIP PROJECTION

The TCO of zero-emission vehicles is anticipated to decline rapidly due to continuous reductions in battery pack costs, research and development (R&D) expenses, warranty costs (i.e., cost of failure), and energy efficiency improvements. Further, this study assumes that the capital cost of ICE vehicles will experience a slight increase over time with tightened fuel efficiency and exhaust emission standards. The rest of the costs are assumed to be constant.

- **The reduction in battery pack costs** is attributed to two factors—a lower unit cost for battery packs and smaller battery capacities due to an improved energy intensity of electric vehicles. The decline in the unit cost for battery packs is captured by the "learning curve" that describes the reduction in unit production costs of battery packs as a function of accumulated production volumes, approximated by electric vehicle sales volumes in this study. Using data on China's battery pack prices and production volumes to perform the regression, we estimated the learning coefficient of unit production costs of battery packs to be -0.26 (learning rate = 17 percent). Our projection for future energy intensity improvements is based on a literature review.

$$Unit\_Cost_{battery\ pack,t} = Unit\_Cost_{battery\ pack,o} \times \left(\frac{V_t}{V_o}\right)^b \quad \text{(Equation 11)}$$

$$Battery\ size_t = Energy\ intensity_t \times Range$$

$$Cost_{battery\ pack,t} = Unit\_Cost_{battery\ pack,t} \times Battery\ size_t$$

where,
b is the learning coefficient
V_t is the production volume in year t
V_o is the production volume in year 0 (the base year of the study)

- **The reduction in the indirect costs for R&D and warranty expenses** are reflected in the falling values of indirect cost multipliers over time. Specifically, we inferred the indirect costs based on the

Table B1 | **Indirect Cost Multiplier for High Technology Complexity**

	SHORT-TERM INDIRECT COST MULTIPLIER	LONG-TERM INDIRECT COST MULTIPLIER
Direct manufacturing cost, including battery packs	1	1
Production overhead		
Warranty	0.12	0.03
R&D	0.2	0.02
Others (e.g., depreciation)	0.1	0.1
Corporate overhead	0.04	0.04
Selling and dealer	0.15	0.07
ICM sum	**1.45**	**1.27**

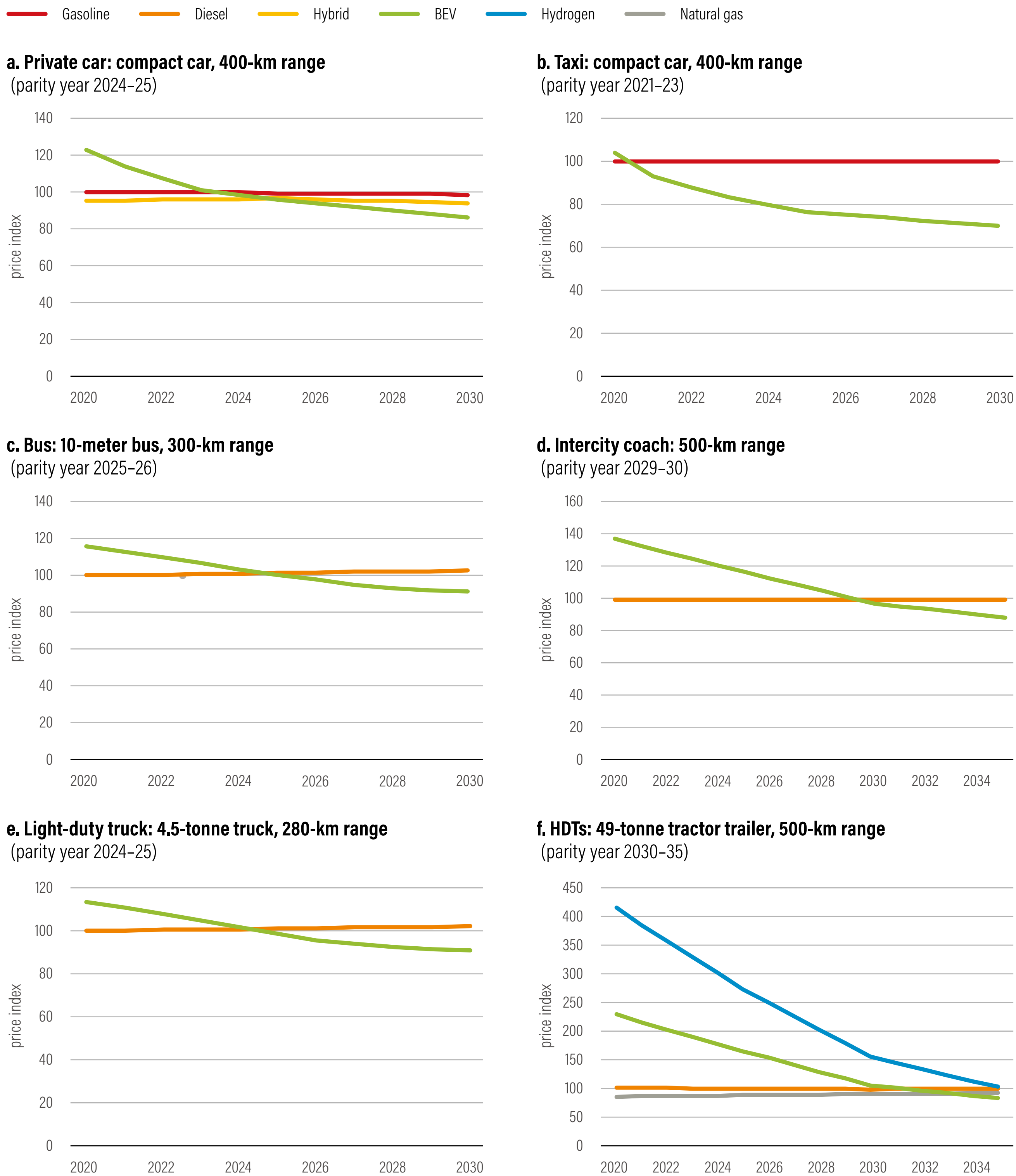
Abbreviations: R&D = research and development; ICM = indirect cost multiplier.
Source: EPA 2009.

linear extrapolation between the short- and long-term indirect cost multipliers used by EPA (2009) (Table B1, Equation 12).

$$Cost_{DMC,t}=Cost_{battery\ pack,t}+Cost_{others}$$
$$Cost_{retail,t}=Cost_{DMC,t}\times ICM_t \quad \text{(Equation 12)}$$

We applied the above methods to all the vehicle segments without considering subsidies or taxes. The TCO results were triangled and adjusted based on existing studies (Mao et al. 2021; Lutsey 2021). The final TCO curves are shown in Figure B1.

Figure B1 | **Lifetime Total Cost of Ownership Projections for the Mainstreamed Vehicle Models of Different Vehicle Segments**



Notes: The 2020 total cost of ownership (TCO) values for ICE vehicles for different segments are scaled to 100, and the rest of the TCO values are scaled accordingly.
Abbreviations: km = kilometer; BEV = battery electric vehicle.
Source: WRI authors' calculation.

APPENDIX C. BIOFUEL CONSIDERATIONS

Biofuels are not considered in the research because their supply, cost, and environmental performance will restrict their future adoption.

First, there are bottlenecks in biofuel feedstock supplies. For example, because of the supply shortage in crops and food security concerns, China's ethanol production was 2.84 million tonnes in 2019, unable to meet the demand of 13 million tonnes if all the gasoline were to be 10 percent blended with ethanol (QDIBBT 2019). Second-generation biofuels[xviii] with different sources of feedstock—mainly from waste and plant cellulose—have similar challenges. By one estimate, the total waste in the United States (including agricultural residue, food waste, sewer sludge, and manure) would generate 22.3 gigaliters/year of biocrude oil and meet only 23.9 percent of current U.S. aviation kerosene demand (Skaggs et al. 2018).

Further, in the absence of policy incentives, the uptake of biofuels would be unlikely to occur. Biofuels are more expensive than fossil fuels: The production cost of biofuels in China is around 5,000–6,000 CNY per ton, about the same as the wholesale price of gasoline/diesel (around 5,200–6,300 CNY).[xix] Strong policy supports would therefore be necessary to promote its adoption. However, a national subsidy to oil refineries for biofuel production (1,883 CNY per tonne in 2005) ended in 2016 due to concern that the large demand for biofuel feedstocks would threaten food security. Further, China has no intention of imposing a quota obligation like the EU's Renewable Energy Directive or the United States' Renewable Fuel Standard, which mandate a minimum share of biofuels (or low-carbon fuels) sold. Last but not the least, the environmental performance of biofuels may not justify public supports. Studies show biodiesel (20 percent blend) increases hydrocarbon and carbon monoxide emissions by 7 percent and 10 percent, respectively (O'Malley and Searle 2021).

ABBREVIATIONS

BEV	battery electric vehicle
CCS	carbon capture and storage
CH_4	methane
CO	carbon monoxide
CNY	Chinese yuan
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GWP	global warming potential
HDT	heavy-duty and medium-duty truck
HFC	hydrofluorocarbon
IAM	integrated assessment model
ICE	internal combustion engine
LNG	liquefied natural gas
N_2O	nitrous oxide
NEV	new energy vehicle
NG	natural gas
NMHC	non-methane hydrocarbons
NOx	nitrogen oxides
PM	particulate matter
SMR	steam methane reforming
TTW	tank to wheel
WTW	well to wheel
WTT	well to tank

ENDNOTES

i. NEVs include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs).

ii. The China 6 emission standard refers to the Stage 6 Limits and Measurement Methods for Emissions from Light-Duty Vehicles (GB18352.6–2016) and the Stage VI Limits and Measurement Methods for Emissions from Heavy-Duty Vehicles (GB17691–2018). China 6 is China's most up-to-date vehicle exhaust emission standard with the air pollutant limits equating to those of Euro 6.

iii. China's NEV policies target passenger carriers, goods carriers, and special purpose vehicles; motorcycles are not included.

iv. Other forms of TCO include the first-owner TCO and second-owner TCO, among others.

v. For charging infrastructure CAPEX, we excluded the expensive grid upgrade investments in the calculation.

vi. A less transport-intensive service sector could play a role in decoupling freight demand from GDP growth.

vii. China's per capita freight demand was 8,000 tkm in 2020, and less than 22,900 tkm per capita in the United States, Australia, and Canada (ITF 2012).

viii. Partly because of the truck industry's overloading and underbidding.

ix. Partly because of the truck industry's overloading and underbidding.

x. Two to three times maximum loading capacity.

xi. The large range is due to different definitions and scopes of TCO in the literature, from first-owner TCO (first 5 to 6 years of useful life) to lifetime TCO (10 to 15 years of useful life).

xii. BEVs are unable to carry high loads over long distances. FCEVs are expensive and fuel cell systems have limited cycle lives.

xiii. New European Driving Cycle (NEDC) (Phases I–IV) and WLTP (Phase V) for passenger cars. C-WTVC for commercial vehicles.

xiv. In 2020, SUVs and multiple purpose vehicles comprised 52 percent of passenger car sales (increasing from 15 percent in 2010) and tractor trailers comprised 45 percent of HDT sales (increasing from 15 percent in 2012).

xv. Fossil fuels include coal, natural gas, and oil products.

xvi. In this study, we considered investments in commercial NEV acquisition and operations as well as capital investments in transit, active mobility, and freight railway infrastructure, all of which are absent in other studies.

xvii. Gasoline particulate filters' overall global warming effect was found to be neutral as the reduction in black carbon (classified as PM10) could counteract the increase in fuel consumption (CO_2 emissions).

xviii. Second-generation biofuels are produced from waste and plant cellulose (such as crop residues) compared with first-generation biofuels, which were produced from crops. The advanced biofuels have many benefits, such as a higher decarbonization potential and alleviation of food-security risks.

xix. For local refineries' wholesale prices in Shandong Province, see https://www.bilibili.com/read/cv12220483.

REFERENCES

Abramczyk, M., M. Campbell, A. Chitkara, M. Diawara, A. Lerch, and J. Newcomb. 2017. *Positive Disruption: Limiting Global Temperature Rise to Well below 2 Degrees*.

ACEA (European Automobile Manufacturers' Association). 2021. *Making the Transition to Zero Emission Mobility.* Progress Report. Brussels: ACEA.

ACEA. 2022. "ACEA Proposals for Euro 7 and Euro VII Emission Standards." https://www.acea.auto/publication/acea-proposals-for-euro-7-and-euro-vii-emission-standards/.

Agenbroad, J., J. Creyts, D. Mullaney, J. Song, and Z. Wang. 2016. *Improving Efficiency in Chinese Trucking and Logistics: Proceeding and Insights from the Design Charrette on Chinese Logistics and Trucking Efficiency Held April 26–27, 2016, in Shenzhen, PRC.* Rocky Mountain Institute.

Agora Energiewende. 2020a. *Towards a Climate-Neutral Germany. Three Steps for Achieving Climate Neutrality by 2050 and an Intermediate Target of -65% in 2030 as Part of the EU Green Deal.* Berlin: Agora Energiewende.

Agora Energiewende. 2020b. *The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition*. Berlin: Agora Energiewende.

ANL (Argonne National Laboratory). 2014. "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model." Lemont, IL: Argonne National Laboratory.

ANL (Argonne National Laboratory). 2018. *China Vehicle Fleet Model: Estimation of Vehicle Stocks, Usage, Emissions, and Energy Use—Model Description, Technical Documentation, and User Guide. Lemont,* IL: Argonne National Laboratory.

ATRI (American Transportation Research Institute). 2020. *An Analysis of the Operational Costs of Trucking: 2020 Update.* Arlington, VA: American Transportation Research Institute.

Autoinfo. 2021. "China Natural Gas Heavy-Duty Vehicle Market Analysis." In Chinese. https://www.autoinfo.org.cn/autoinfo_cn/content/news/20210508/3033391.html.

BCG (Boston Consulting Group). 2020. *Climate Plan for China*. Boston: Boston Consulting Group.

BloombergNEF. 2021. *Electric Vehicle Outlook 2021.* New York: BloombergNEF.

BTS (Bureau of Transportation Statistics, United States). 2021a. *National Transportation Statistics 2021.* Washington, DC: Bureau of Transportation Statistics.

BTS. 2021b. *Hybrid-Electric, Plug-In Hybrid-Electric and Electric Vehicle Sales*. Washington, DC: Bureau of Transportation Statistics.

BTS and FHWA (Federal Highway Administration, United States). 2016. *The 4th Generation Freight Analysis Framework (FAF4) for Freight Volume Forecast for 2020 through 2045.* Washington, DC: Bureau of Transportation Statistics and Federal Highway Administration.

CAAM (China Association of Automobile Manufacturers). 2012. *2011 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2013. *2012 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2014. *2013 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2015. *2014 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2016. *2015 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2017. *2016 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2018. *2017 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2019. *2018 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2020. *2019 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2021a. *2020 Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2021b. *Monthly Report on Automobile Industry Operation—November of 2021.* Beijing: China Association of Automobile Manufacturers.

CAAM. 2022. 2021 *Progress Report on China's Automobile Industry.* Beijing: China Association of Automobile Manufacturers.

CAM (China Association of Metros). 2017. *China Urban Rail Transit Annual Statistics and Analysis 2017.* Beijing: China Association of Metros.

CAM. 2018. *China Urban Rail Transit Annual Statistics and Analysis 2018.* Beijing: China Association of Metros.

CAM. 2019. *China Urban Rail Transit Annual Statistics and Analysis 2019.* Beijing: China Association of Metros.

CAM. 2020. *China Urban Rail Transit Annual Statistics and Analysis 2020.* Beijing: China Association of Metros.

CARB (California Air Resources Board). 2020. *Advanced Clean Trucks Regulation.* Sacramento, CA: CARB.

CATARC (China Automotive Technology and Research Center). 2016. *Annual Report on Energy-Saving and New Energy Vehicles in China 2016.* Tianjin, China: China Automotive Technology and Research Center.

CATARC. 2018. *Annual Report on Energy-Saving and New Energy Vehicles in China 2018.* Tianjin, China: China Automotive Technology and Research Center.

CATARC. 2021. *Annual Report on Energy-Saving and New Energy Vehicles in China 2021.* Tianjin, China: China Automotive Technology and Research Center.

CEC (China Electricity Council). 2020. *China 2020 Electricity and Industry Operation Bulletin.* Beijing: CEC.

CHA (China Hydrogen Alliance). 2019. *White Paper on China Hydrogen Energy Carrier and Fuel Cell Stack Industry 2019.* Beijing: China Hydrogen Alliance.

China EV 100 and NRDC (Natural Resources Defense Council). 2019. *How to Enable the Healthy Development of the Electric Vehicle Charging Market in China?*

China SAE (China Society of Automotive Engineers). 2020. *Technology Roadmap for Energy-Saving and New Energy Vehicles 2.0 (The Roadmap)*. Beijing: China Machine Press.

China Transport News. 2021. "Shenzhen Prioritizes Green Transport and Revitalize the City." https://www.mot.gov.cn/jiaotongyaowen/202112/t20211207_3630018.html.

Clairotte, M., R. Suarez-Bertoa, A.A. Zardini, B. Giechaskiel, J. Pavlovic, V. Valverde, B. Ciuffo, et al. 2020. "Exhaust Emission Factors of Greenhouse Gases (GHGs) from European Road Vehicles." *Environ Sci Eur* 32 (125). https://doi.org/10.1186/s12302-020-00407-5.

Climate Watch. 2020. (Database.) "Global Historical GHG Emissions-CAIT." Washington, DC: World Resources Institute. https://www.climatewatchdata.org.

CSI (China Standardization Institute). 2018. *China Hydrogen Industry Infrastructure Development Bluebook (2016)*. Beijing: China Quality and Standard Publishing.

DOE (United States Department of Energy). 2020. *Hydrogen Strategy: Enabling a Low-Carbon Economy.* Washington, DC: DOE.

DOT (United Kingdom Department of Transport). 2021. *Consultation on When to Phase Out the Sale of New, Non-zero Emission Heavy Goods Vehicles.* London: United Kingdom Department of Transport.

Edelenbosch, O.Y., D.P. van Vuuren, C. Bertram, S. Carrara, J. Emmerling, H. Daly, A. Kitous, et al. 2017. "Transport Fuel Demand Responses to Fuel Price and Income Projections: Comparison of Integrated Assessment Models." *Transportation Research Part D—Transport and Environment* 55: 310–21.

EEA (European Environment Agency). 2020. "EEA Greenhouse Gases—Data Viewer." Copenhagen: EEA.

Enoch, M. 2018. *Mobility as a Service (MaaS) in the UK: Change and Its Implications.* Loughborough, United Kingdom: School of Architecture, Building and Civil Engineering, Loughborough University.

EPA (United States Environmental Protection Agency). 2009. *Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers.* Washington, DC: EPA.

EPA. 2015. *Transitioning to Low-GWP Alternatives in Passenger Vehicle Air Conditioners.* Washington, DC: EPA.

EPA. 2020. "Greenhouse Gas Inventory Data Explorer." Washington, DC: EPA. https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

ERTICO (ERTICO – ITS Europe, Editor). 2019. *Mobility as a Service (MaaS) and Sustainable Urban Mobility Planning*.

EU P&C (European Union Parliament and Council). 2019. *Regulation (Eu) 2019/631 of the European Parliament and of the Council. Setting CO_2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011.*

Eurostat. 2021a. "Stock of Vehicles by Category and NUTS 2 Regions." Luxembourg City: Eurostat.

Eurostat. 2021b. "Freight Transported in Containers — Statistics on Unitisation." Luxembourg City: Eurostat.

Eurostat. 2021c. "Annual Road Freight Transport by Load Capacity of Vehicle." Luxembourg City: Eurostat.

Eurostat. 2021d. "Road Freight Transport Statistics." Luxembourg City: Eurostat.

Eurostat. 2021e. "Lorries and Lorries (Excluding Light Goods Road Vehicles)." Luxembourg City: Eurostat.

Feng, J., Y. Zhang, S. Li, J. Mao, A.P. Patton, Y. Zhou, W. Ma, et al. 2019. "The Influence of Spatiality on Shipping Emissions, Air Quality and Potential Human Exposure in the Yangtze River Delta/Shanghai, China." *Atmos. Chem. Phys.* 19 (9): 6167–83. https://doi.org/10.5194/acp-19-6167-2019.

FHWA (Federal Highway Administration, United States). 2021. "Highway Statistics 2019—Annual Vehicle Distance Traveled in Miles and Related Data by Highway Category and Vehicle Type." Washington, DC: FHWA.

Fransen, T., B. Welle, C. Gorguinpour, M. McCall, R. Song, and A. Tankou. 2019. "Enhancing NDCs: Opportunities in Transport." Working Paper. Washington, DC: World Resources Institute.

Frey, K., J. Hartwig, and C. Doll. 2014. "Accelerating a Shift from Road to Rail Freight Transport in Germany: Three Scenarios." *Transport Research Arena 2014, Paris.*

Fu, Z.H., et al. 2019. *Strategy Research on Transportation Power.* Beijing: China Communications Press. Co. Ltd.

Gao, Z.M., T.J. LaClair, D.E. Smith, and C. Stuart Daw. 2015. "Exploring Fuel-Saving Potential of Long-Haul Truck Hybridization." *Transportation Research Record* 2502 (2502): doi:10.3141/2502-12.

Gao, Z., T. Laclair, S. Ou, S. Huff, G. Wu, P. Hao, K. Boriboonsomsin, et al. 2019. "Evaluation of Electric Vehicle Component Performance over Eco-driving Cycles." *Energy* 172: 823–39. https://doi.org/10.1016/j.energy.2019.02.017.

Gilbert, C. 2017. Global Passenger Car Penetration: *Grid Lock!* Legal & General Investment Management Limited.

Gnann, T., P. Plötz, A. Kühn, and M. Wietschel. 2017. *How to Decarbonize Heavy Road Transport?* ECEEE 2017 Summer Study—Consumption, Efficiency & Limits.

Goldman Sachs. 2021. *Carbonomics—China Net Zero: The Clean Tech Revolution.* New York: Goldman Sachs.

Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker. 2018. "Decarbonising Transport to Achieve Paris Agreement Targets." *Energy Efficiency* 12: 363–86. https://doi.org/10/gfpm72.

Gustafsson, M., N. Svensson, M. Eklund, J. Dahl Öberg, and A. Vehabovic. 2021. "Well-to-Wheel Greenhouse Gas Emissions of Heavy-Duty Transports: Influence of Electricity Carbon Intensity." *Transportation Research Part D: Transport and Environment* 93: 102757. ISSN 1361-9209. https://doi.org/10.1016/j.trd.2021.102757.

Hao, H., Y. Geng, W.Q. Li, and B. Guo. 2015. "Energy Consumption and GHG Emissions from China's Freight Transport Sector: Scenarios through 2050." *Energy Policy* 85: 94–101. ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2015.05.016.

Heaps, C.G. 2022. LEAP: The Low Emissions Analysis Platform. [Software version: 2020.1.56]. Somerville, MA: Stockholm Environment Institute. https://leap.sei.org.

HPK. 2019. "Efficiency and CO_2 Emission Analysis of Internal Combustion Engines (ICE) and Electric Vehicles (EV) on WTT and TTW Emissions." Future #SmartMobility Needs Sustainable #CleanEnergy Blog. https://kleebinder.net/en/tag/lifecycle-assessment/.

Hu, T., X.Q. Mao, X.D. Lu, and P. Gerilla-Teknomo. 2020. *Air Pollutants and Greenhouse Gas Emissions Co-control Evaluation in the People's Republic of China.* ADB East-Asia Working Paper Series. Manila: Asian Development Bank.

Huo, H., M. Wang, X.L. Zhang, K. He, H. Gong, K. Jiang, Y. Jing, et al. 2012a. "Projection of Energy Use and Greenhouse Gas Emissions by Motor Vehicles in China: Policy Options and Impacts." *Energy Policy* 43 (C): 37–48.

Huo, H., Q. Zhang, K.B. He, Z.Z. Yao, and M. Wang. 2012b. "Vehicle-Use Intensity in China: Current Status and Future Trend." Energy Policy 43 (C): 6–16.

ICCSD (Institute of Climate Change and Sustainable Development of Tsinghua University). 2020. *China's Long-Term Low-Carbon Development Strategies and Pathways: Comprehensive Report.* Beijing: China Environment Press.

ICCT (International Council on Clean Transportation). 2017. *China's Stage 6 Emission Standard for New Light-Duty Vehicles (Final Rule).* ICCT 2017 Policy Update. Beijing: ICCT.

ICCT. 2019. "Comments on China's Proposed 2021–2025 Fuel Consumption Limits, Evaluation Methods, and Targets for Passenger Cars." Beijing: ICCT.

iCET (Innovation Center for Energy and Transportation). 2017. *Annual Report on the Differences between Real-World Fuel Consumption and Certified Fuel Consumption for Passenger Cars.* Beijing: iCET.

iCET. 2021. *Report on China's Commercial Vehicle Electrification Potentials.* Beijing: iCET.

IEA (International Energy Agency). 2021a. *World Energy Outlook 2021.* Paris: IEA.

IEA. 2021b. *An Energy Sector Roadmap to Carbon Neutrality in China.* Paris: IEA.

IPCC (Intergovernmental Panel on Climate Change). 2006. *Guidelines for National Greenhouse Gas Inventories.* Geneva: IPCC.

IPCC. 2014. *Climate Change 2014: Synthesis Report.* Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team: R.K. Pachauri and L.A. Meyer (Eds.)]. Geneva: IPCC.

IRENA (International Renewable Energy Agency). 2020. *Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal.* Abu Dhabi: IRENA.

ITF (International Transport Forum). 2012. (Database.) *OECD. Stat.* Paris: ITF. http://stats.oecd.org/index.aspx.

ITF. 2013. *Railway Efficiency: An Overview and a Look at Opportunities for Improvement.* ITF Discussion Paper No. 201312. Paris: ITF. https://www.itf-oecd.org/sites/default/files/docs/dp201312.pdf.

ITF. 2019. *ITF Transport Outlook 2019.* Paris: ITF.

MLITT (Ministry of Land Infrastructure Transport and Tourism, Japan). 2021. 統計情報. https://www.mlit.go.jp/statistics/details/jidosha_list.html.

Jiang, X.Q., W.Y. Xi, W.K. Fong, J.Y. Song, and Z. Wang. 2019. *Wuhan Transport Sector Carbon Emissions Roadmap Study.* Washington, DC: World Resources Institute.

Kaak, L.H., P. Vaishanav, M.G. Morgan, I. Azevedo, and S. Rai. 2018. "Decarbonizing Intraregional Freight Systems with a Focus on Modal Shift." *Environmental Research Letters* 13 (8).

Kong, H., X.H. Zhang, and J.H. Zhao. 2020. "How Does Ridesourcing Substitute for Public Transit? A Geospatial Perspective in Chengdu, China." *Journal of Transport Geography* 86: 102769. ISSN 0966-6923. https://doi.org/10.1016/j.jtrangeo.2020.102769.

Lai, J. n.d. "Bus Rationalization in Hong Kong." Presentation. Metropolis. https://www.metropolis.org/sites/default/files/hong-kong_bus-rationalization.pdf.

LBNL (Lawrence Berkeley National Laboratory). 2021. *Assessment of Energy Strategies for China's Heavy-Duty Trucks and the Potential for Electrification.* Berkeley, CA: Lawrence Berkeley National Laboratory.

Ledna, C., M. Muratori, A. Yip, P. Jadun, and C. Hoehne. 2022. "Decarbonizing Medium- and Heavy-Duty On-Road Vehicles: Zero Emission Vehicles Cost Analysis." Presentation. Golden, CO: National Renewable Energy Laboratory.

Le Quéré, C., R.B. Jackson, M.W. Jones, A.J.P. Smith, S. Abernethy, R.M. Andrew, A.J. De-Gol, et al. 2020. "Temporary Reduction in Daily Global CO_2 Emissions during the COVID-19 Forced Confinement." *Nat. Clim. Chang*. 10: 647–53. https://doi.org/10.1038/s41558-020-0797-x.

Liang, B., Y. Ge, J. Tan, X. Han, L. Gao, L. Hao, W. Ye, and P. Dai. 2012. "Comparison of PM Emissions from a Gasoline Direct Injected (GDI) Vehicle and a Port Fuel Injected (PFI) Vehicle Measured by Electrical Low Pressure Impactor (ELPI) with Two Fuels: Gasoline and M15 Methanol Gasoline." *Journal of Aerosol Science* 57: 22–31.

Liimatainen, H., O. Vliet, and D. Aplyn. 2019. "The Potential of Electric Trucks—An International Commodity-Level Analysis." *Applied Energy* 236: 804–14.

Liu, F.Q., D.L. Mauzerall, F. Zhao, and H. Hao. 2021. "Deployment of Fuel Cell Vehicles in China: Greenhouse Gas Emission Reductions from Converting the Heavy-Duty Truck Fleet from Diesel and Natural Gas to Hydrogen." *International Journal of Hydrogen Energy* 46 (34): 17982–97. https://doi.org/10.1016/j.ijhydene.2021.02.198.

Liu, H.H. 2018. "China Railway Beijing Group's Reflections on Price Signals to Facilitate Freight Mode Shift from Roadways to Railways." *Railway Economic Research* 05: 5–10.

Liu, J.L., Y.H. Sun, K. Wang, J. Zou, and Y. Kong. 2018. "Study on Mid- and Long-Term Low Carbon Development Pathway for China's Transport Sector." *Climate Change Research* 14 (5): 513–21.

Liu, J.L., M. Yin, Q. Xia-Hou, K. Wang, and J. Zou. 2021. "Comparison of Sectoral Low-Carbon Transition Pathways in China under the Nationally Determined Contribution and 2°C Targets." *Renewable and Sustainable Energy Reviews* 149. ISSN 1364-0321. https://doi.org/10.1016/j.rser.2021.111336.

LTA (Singapore Land Transport Authority Singapore). 2021. "Annual Vehicle Statistics 2021 (Motor Vehicle Population by Vehicle Type)."

Lutsey, N., H.Y. Cui, and R.J. Yu. 2021. *Evaluating Electric Vehicle Costs and Benefits in China in the 2020–2035 Time Frame*. White Paper. Beijing: International Council on Clean Transportation.

Mamakos, A. 2011. *Feasibility of Introducing Particulate Filters on Gasoline Direct Injection Vehicles: A Cost Benefit Analysis.* JRC Scientific and Policy Reports. Luxembourg: Publications Office of the European Union.

Mao, S., H. Basma, P.–L. Ragon, Y. Zhou, and F. Rodríguez. 2021. *Total Cost of Ownership for Heavy Trucks in China: Battery Electric, Fuel Cell Electric and Diesel Trucks.* White Paper. Beijing: International Council on Clean Transportation.

Mareev, I., J. Becker, and D. Sauer. 2018. "Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation." *Energies* 11 (1): 55.

McKinnon, A. 2010. *European Freight Transport Statistics: Limitations, Misinterpretations, and Aspirations*. Report prepared for the 15th European Automobile Manufacturers' Association Scientific Advisory Group Meeting. Brussels, September 8.

MEE (Ministry of Ecology and Environment, China). 2011. *China Vehicle Environmental Management Annual Report 2011*. Beijing: China Ministry of Ecology and Environment.

MEE. 2012. *China Vehicle Environmental Management Annual Report 2012.* Beijing: China Ministry of Ecology and Environment.

MEE. 2013. *China Vehicle Environmental Management Annual Report 2013.* Beijing: China Ministry of Ecology and Environment.

MEE. 2014a. *China Vehicle Environmental Management Annual Report 2014.* Beijing: China Ministry of Ecology and Environment.

MEE. 2014b. *China's National Guide on Road Transport Air Pollutant Inventory Development (Test Version)*. Beijing: China Ministry of Ecology and Environment.

MEE. 2015. *China Vehicle Environmental Management Annual Report 2015.* Beijing: China Ministry of Ecology and Environment.

MEE. 2016. *China Vehicle Environmental Management Annual Report 2016.* Beijing: China Ministry of Ecology and Environment.

MEE. 2017. *China Vehicle Environmental Management Annual Report 2017.* Beijing: China Ministry of Ecology and Environment.

MEE. 2018a. *China's Second Biennial Update Report on Climate Change.* Beijing: China Ministry of Ecology and Environment.

MEE. 2018b. *The People's Republic of China Third National Communication on Climate Change.* Beijing: China Ministry of Ecology and Environment.

MEE. 2018c. *China Vehicle Environmental Management Annual Report 2018.* Beijing: China Ministry of Ecology and Environment.

MEE. 2018d. "The State Council Rolls Out a Three-Year Action Plan for Clean Air." https://english.mee.gov.cn/News_service/news_release/201807/t20180713_446624.shtml.

MEE. 2019. *China Vehicle Environmental Management Annual Report 2019.* Beijing: China Ministry of Ecology and Environment.

MEE. 2020a. *China Vehicle Environmental Management Annual Report 2020.* Beijing: China Ministry of Ecology and Environment.

MEE. 2020b. *Bulletin on the Second National Census of Pollution Source.* Beijing: China Ministry of Ecology and Environment.

MEE. 2021. *China Vehicle Environmental Management Annual Report 2021.* Beijing: China Ministry of Ecology and Environment.

MIIT (Ministry of Industry and Information Technology, China). 2019. *Fuel Consumption Evaluation Methods and Targets for Passenger Cars (GB 27999-2019)*. Beijing: China Ministry of Industry and Information Technology.

MIIT. 2021. *Fuel Consumption Limits for Passenger Cars (GB19578-2021).* Beijing: China Ministry of Industry and Information Technology.

MOT (Ministry of Transport of China). 2015. *The 13th Five-Year Plan on Comprehensive Transport Development.* Beijing: Ministry of Transport of China.

MOT. 2016. *China Annual Transport Statistical Bulletin 2016.* Beijing: Ministry of Transport of China.

MOT. 2017a. *Regularity of the Enforcement on Vehicle Overloading.* Beijing: Ministry of Transport of China.

MOT. 2017b. *Guideline on Management of Illegal Adaptations to Vehicles and Vehicle Overloading.* Beijing: Ministry of Transport of China.

MOT. 2019. *Interim Measures for the Operation and Administration of Road Freight Transport Based on Internet Platforms.* Beijing: Ministry of Transport of China.

Mottschall, M., P. Kasten, and F. Rodriguez. 2020. *Decarbonization of On-Road Freight Transport and the Role of LNG from a German Perspective.* Beijing: International Council on Clean Transportation.

MPS (Ministry of Public Security, China). 2019. "Road Traffic Management—Types of Motor Vehicles (GA802–2019)." China Public Security Sectoral Standard. Beijing: Ministry of Public Security.

Mulholland, E., J. Teter, P. Cazzola, Z. McDonald, and B.P. Ó Gallachóir. 2018. "The Long Haul towards Decarbonising Road Freight—A Global Assessment to 2050." *Applied Energy* 216 (C): 678–93.

NBS (National Bureau of Statistics of China). 2002. *China Statistical Yearbook 2002*. Beijing: National Bureau of Statistics of China.

NBS. 2003. *China Statistical Yearbook 2003*. Beijing: National Bureau of Statistics of China.

NBS. 2004. *China Statistical Yearbook 2004.* Beijing: National Bureau of Statistics of China.

NBS. 2005. *China Statistical Yearbook 2005*. Beijing: National Bureau of Statistics of China.

NBS. 2006. *China Statistical Yearbook 2006.* Beijing: National Bureau of Statistics of China.

NBS. 2007. *China Statistical Yearbook 2007.* Beijing: National Bureau of Statistics of China.

NBS. 2008. *China Statistical Yearbook 2008.* Beijing: National Bureau of Statistics of China.

NBS. 2009. *China Statistical Yearbook 2009.* Beijing: National Bureau of Statistics of China.

NBS. 2010. *China Statistical Yearbook 2010.* Beijing: National Bureau of Statistics of China.

NBS. 2011. *China Statistical Yearbook 2011.* Beijing: National Bureau of Statistics of China.

NBS. 2012. *China Statistical Yearbook 2012.* Beijing: National Bureau of Statistics of China.

NBS. 2013. *China Statistical Yearbook 2013.* Beijing: National Bureau of Statistics of China.

NBS. 2014. *China Statistical Yearbook 2014.* Beijing: National Bureau of Statistics of China.

NBS. 2015. *China Statistical Yearbook 2015.* Beijing: National Bureau of Statistics of China.

NBS. 2016. *China Statistical Yearbook 2016.* Beijing: National Bureau of Statistics of China.

NBS. 2017. *China Statistical Yearbook 2017.* Beijing: National Bureau of Statistics of China.

NBS. 2018. *China Statistical Yearbook 2018.* Beijing: National Bureau of Statistics of China.

NBS. 2019. *China Statistical Yearbook 2019.* Beijing: National Bureau of Statistics of China.

NBS. 2020. *China Statistical Yearbook 2020.* Beijing: National Bureau of Statistics of China.

NBS. 2021. *China Statistical Yearbook 2021.* Beijing: National Bureau of Statistics of China.

NCI and CA (New Climate Institute and Climate Analytics). 2020. *Climate Action Tracker: Paris Agreement Compatible Sectoral Benchmarks. Methods Report on Elaborating the Decarbonisation Roadmap.*

NDRC (National Development and Reform Commission, China). 2004. *The People's Republic of China Initial National Communication on Climate Change.* Beijing: China National Development and Reform Commission.

NDRC. 2012. *The People's Republic of China Second National Communication on Climate Change.* Beijing: China National Development and Reform Commission.

NDRC. 2016. *China's First Biennial Update Report on Climate Change.* Beijing: China National Development and Reform Commission.

NDRC. 2021. *Action Plan for Carbon Dioxide Peaking before 2030*. Beijing: China National Development and Reform Commission. https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html.

Ntziachristos, L., D. Gkatzoflias, C. Kouridis, and Z. Samaras. 2009. "COPERT: A European Road Transport Emission Inventory Model." In I.N. Athanasiadis, A.E. Rizzoli, P.A. Mitkas, J.M. Gómez (Eds.). *Information Technologies in Environmental Engineering.* Environmental Science and Engineering. Berlin, Heidelberg: Springer.

O'Driscoll, R., M. Stettler, N. Molden, T. Oxley, and H.M. ApSimon. 2018. "Real World CO_2 and NOx Emissions from 149 Euro 5 and 6 Diesel, Gasoline and Hybrid Passenger Cars." *Science of the Total Environment* 621: 282–90.

OECD (Organisation for Economic Co-operation and Development). n.d. "Freight Transport (Indicator)." Paris: OECD. doi: 10.1787/708eda32-en. Accessed April 20, 2022.

OECD. 2018. *Total Inland Transport Infrastructure Investment per GDP.* Paris: OECD.

O'Malley, J., and S. Searle. 2021. *Air Quality Impacts of Biodiesel in the U.S.* White Paper. Beijing: International Council on Clean Transportation.

Pan, D., L. Tao, K. Sun, L.M. Golston, D.J. Miller, T. Zhu, Y. Qin, et al. 2020. "Methane Emissions from Natural Gas Vehicles in China." *Nature Communication* 11 (4588). https://doi.org/10.1038/s41467-020-18141-0.

Pan, X., H.L. Wang, L.N. Wang, and W. Chen. 2018. "Decarbonization of China's Transportation Sector: In Light of National Mitigation toward the Paris Agreement Goals." *Energy* 155: 853–64. ISSN 0360-5442. https://doi.org/10.1016/j.energy.2018.04.144.

Peng, L.Q., F.Q. Liu, M. Zhou, M. Li, Q. Zhang, and D.L. Mauzerall. 2021. "Alternative-Energy-Vehicles Deployment Delivers Climate, Air Quality, and Health Co-benefits when Coupled with Decarbonizing Power Generation in China." *One Earth* 4: 1127–40.

Phadke, A., A. Khandekar, N. Abhyankar, D. Wooley, and D. Rajagopal. 2021. "Why Regional and Long-Haul Trucks Are Primed for Electrification Now." Berkeley, CA: Lawrence Berkeley National Laboratory.

QDIBBT (Qindao Institute of BioEnergy and Bioprocess Technology, China Academy of Sciences). 2019. "Not Living Up to Expectations: China Has Ethanol Supply Gaps." http://www.qibebt.cas.cn/xwzx/kydt/201903/t20190316_5257518.html.

Qiu, S.Y., L.L. Xue, J. Cai, J.Q. Chen, L.Y. Song, and Z. Wu. 2020. "Zero-Emission Logistic Vehicles Promotion Challenges and Experiences: Beijing Case Study." Working Paper. Beijing: WRI China.

Riahi, K., F. Dentener, D. Gielen, A. Grubler, J. Jewell, Z. Klimont, V. Krey, et al. 2012. "Energy Pathways for Sustainable Development." In *Global Energy Assessment: Toward a Sustainable Future*, edited by T.B. Johansson, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri. Cambridge: Cambridge University Press.

RIOH and Sinoiov (Research Institute of Highway of China and Sinoiov). 2021. *Big Data Based China Road Freight Industry Operation Analysis Report (2020).* Beijing: Research Institute of Highway of China and Sinoiov.

Saliba, G., R. Saleh, Y. Zhao, A.A. Presto, A.T. Lambe, B. Frodin, S. Sardar, et al. 2017. "Comparison of Gasoline Direct-Injection (GDI) and Port Fuel Injection (PFI) Vehicle Emissions: Emission Certification Standards, Cold-Start, Secondary Organic Aerosol Formation Potential, and Potential Climate Impacts." *Environment Science Technology* 51 (11): 6542–52.

Schaller, B. 2021. "Can Sharing a Ride Make for Less Traffic? Evidence from Uber and Lyft and Implications for Cities." *Transport Policy* 102: 1–10. ISSN 0967-070X. https://doi.org/10.1016/j.tranpol.2020.12.015.

Schroten, A., G. Warringa, and M. Bles. 2012. *Marginal Abatement Cost Curves for Heavy Duty Vehicles.* Background Report. Delft, Netherlands: CE Delft.

SFC (Smart Freight Center). n.d. *Smart Freight Forum: China Modal Shift from Truck to Rail Summary Report.*

Shao, Y.Z. 2020. "Environmental Impacts of Modal Shift to Rail in Tangshan." Working Paper. Beijing: International Council on Clean Transportation.

Shao, Y.Z. 2021. *The Updated China IV Non-road Emission Standards. Policy Update.* Beijing: International Council on Clean Transportation. https://theicct.org/publications/china-iv-non-road-emission-standards-jul2021.

Skaggs, R.L., A.M. Coleman, T.E. Seiple, and A.R. Milbrandt. 2018. "Waste-to-Energy Biofuel Production Potential for Selected Feedstocks in the Conterminous United States." *Renewable and Sustainable Energy Reviews* 82 (3): 2640–51. ISSN 1364-0321. https://doi.org/10.1016/j.rser.2017.09.107.

Song, S. 2017. *The Transport Emissions & Social Cost Assessment.* Washington, DC: World Resources Institute.

Spielmann, M., M. Faltenbacher, A. Stoffregen, and D. Eichhorn. 2010. *Comparison of Energy Demand and Emissions from Road, Rail and Waterway Transport in Long-Distance Freight Transport.* Leinfelden-Echterdingen, Germany: PE International.

State Council (State Council, the People's Republic of China). 2020. *NEV Industrial Development Plan 2021–35.* Beijing: State Council.

State Council. 2021a. *Guideline on Further Prevention and Control of Pollution (2021–25)*. Beijing: State Council.

State Council. 2021b. *National Comprehensive Three-Dimensional Transportation Network (2021–35)*. Beijing: State Council.

T&E (Transport & Environment). 2020a. *Compressed Natural Gas Vehicles Are Not a Clean Solution for Transport: Review of the Latest Evidence Shows High Levels of Particle Emissions.* Brussels: Transport & Environment. https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_06_TE_CNG_particle_report.pdf.

T&E. 2020b. *How to Decarbonize the UK's Freight Sector by 2050.* Brussels: Transport & Environment.

Teske, S., S. Niklas, and R. Langdon. 2021. *TUMI Transport Outlook 1.5°C: A Global Scenario to Decarbonize Transport*. Bonn, Germany: Transformative Urban Mobility Initiative.

UK DfT (Department for Transport, United Kingdom). 2021. *Decarbonizing Transport: A Better, Greener Britain*. London: Department for Transport.

Wang, H.L., X.M. Ou, and X.L. Zhang. 2017. "Mode, Technology, Energy Consumption, and Resulting CO_2 Emissions in China's Transport Sector up to 2050." *Energy Policy* 109: 719–33. ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2017.07.010.

Wang, H., J.Y. Han, M. Su, S.L. Wan, and Z.C. Zhang. 2021. "The Relationship between Freight Transport and Economic Development: A Case Study of China." *Research in Transportation Economics* 85: 100885. ISSN 0739-8859. https://doi.org/10.1016/j.retrec.2020.100885.

Wang, Z.P., Z.W. Yao, et al. 2021. *Annual Report on the Big Data of New Energy Vehicles in China (2021)*. Beijing: China Machine Press.

Wappelhorst, S. 2021. "Update on Government Targets for Phasing Out New Sales of Internal Combustion Engine Passenger Cars." Briefing. Beijing: International Council on Clean Transportation.

Wappelhorst, S., U. Tietge, G. Bieker, and P. Mock. 2021. "Europe's CO_2 Emission Performance Standards for New Passenger Cars: Lessons from 2020 and Future Prospects." Working Paper. Beijing: International Council on Clean Transportation.

Wei, H.Y., H. Zhou, Y. Yan, et al. 2020. "The Development of Diesel Fueled Heavy-Duty Vehicle Emission Standards in China." *Small Internal Combustion Engine and Vehicle Technique* 49 (06):79–87.

WHO (World Health Organization). 2021. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide.* Geneva: WHO. https://apps.who.int/iris/handle/10665/345329. License: CC BY-NC-SA 3.0 IGO.

World Bank. 2021. *Electrification of Public Transport: A Case Study of the Shenzhen Bus Group.* Mobility and Transport Connectivity. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35935 License: CC BY 3.0 IGO.

Xinhua News. 2020. "China E-scooters' Stock Approaching 300 Million." http://www.gov.cn/xinwen/2020-11/20/content_5562997.htm.

Xinhua News. 2021. "Beijing City Center's Green Transport Mode Share over 73%." http://www.gov.cn/xinwen/2020-11/20/content_5562997.htm.

Xue, L.L., J. Liu, Y. Wang, X.S. Liu, and X. Ying. 2020. *Action Plans and Policy Recommendations on Vehicle Grid Integration in China.* Washington, DC: World Resources Institute.

Xue, L.L., Y.N. Jin, R.J. Yu, Y. Liu, and H. Ren. 2019. "Toward 'Net Zero' Emissions in the Road Transport Sector in China." Working Paper. Washington, DC: World Resources Institute.

Yang, L.H., O. Delgado, and R. Muncrief. 2019. "Barriers and Opportunities for Improving Long-Haul Freight Efficiency in China." Beijing: International Council on Clean Transportation.

Yang, Z.F., and H.Y. Cui. 2020. *Technology Roadmap and Costs for Fuel Efficiency Increase and CO_2 Reduction from Chinese New Passenger Cars in 2030.* Beijing: International Council on Clean Transportation.

Yeh, S., G.S. Mishra, L. Fulton, P. Kyle, D. McCollum, J. Miller, P. Cazzola, et al. 2017. "Detailed Assessment of Global Transport-Energy Models' Structures and Projections." *Transportation Research Part D: Transport and Environment* 55: 294–309. ISSN 1361-9209. https://doi.org/10.1016/j.trd.2016.11.001.

Yin, X., W.Y. Chen, Y.J. Eom, L.E. Clarke, S.H. Kim, P.L. Patel, S. Yu, et al. 2015. "China's Transportation Energy Consumption and CO_2 Emissions from a Global Perspective." *Energy Policy* 82: 233–48. ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2015.03.021.

Zhang, H.J., W.Y. Chen, and W.L. Huang. 2016. "TIMES Modelling of Transport Sector in China and USA: Comparisons from a Decarbonization Perspective." *Applied Energy* 162: 1505-1514.

Zhang, H., J. Chen, W. Li, X. Song, and R. Shibasaki. 2020. "Mobile Phone GPS Data in Urban Ride-Sharing: An Assessment Method for Emission Reduction Potential." *Applied Energy* 269: 115038. https://doi.org/10.1016/j.apenergy.2020.115038.

Zhou, H.Y., Y.C. Wang, and J.R. Huscroft. 2020. “Impacts of COVID-19 on the Transportation Sector: A Report on China.” SSRN. http://dx.doi.org/10.2139/ssrn.3679662.

ZTB (Zhuzhou Transport Bureau). 2017. *Zhuzhou Annual Transport Development Report*. Zhuzhou, China: Zhuzhou Transport Bureau.

ABOUT THE AUTHORS

Lulu Xue, China Mobility Manager, WRI China. Contact: Lxue@wri.org

Daizong Liu, China Sustainable Cities Director, WRI China.

ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

PHOTO CREDITS

Cover Harry Zhang; pg. i Unsplash/JJ Ying; pg. ii Harry Zhang;
pg. iv Harry Zhang; pg. x Unsplash/David Veksler; pg. x Harry Zhang;
pg. xi Harry Zhang; pg.xi Unsplash/Decry.Yae; pg.xii, Harry Zhang;
pg. 3 Unsplash/Zhang gc; pg. 6 Unsplash/Kevin Grieve; pg. 14 Harry Zhang;
pg. 15 Zhao Yanrong; pg. 17 Harry Zhang; pg. 18 Unsplash/zhang kaiyv;
pg. 31 Harry Zhang; pg. 42 Unsplash/Jerry Wang;
pg. 67 Unsplash/LUFANG CAO; pg. 68 Unsplash/Luca Deasti;
pg. 71 Unsplash/billow926; pg. 72 Unsplash/Decry.Yae.

世界资源研究所
WORLD RESOURCES INSTITUTE

WRI CHINA
RM K-M, 7/F, TOWER A, THE EAST GATE PLAZA,
#9 DONGZHONG STREET, BEIJING, CHINA, 100027
PHONE: 86 10 6416 5697
FAX:86 10 6416 7567
WWW.WRI.ORG.CN