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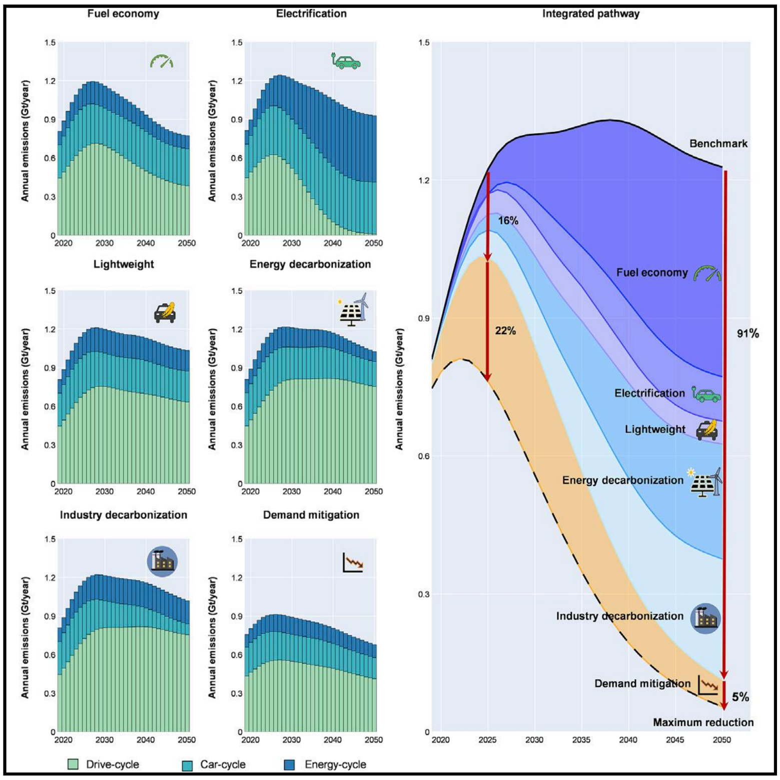
Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions

Graphical abstract



Highlights

- Reducing CO_2 of China's passenger cars must coordinate both demand and technology side
- Technology-side strategies enable long-term CO_2 reduction by 91% in 2050
- Demand-side strategies lead near-term CO_2 reduction by 22% in 2025
- Demand- and technology-side strategies can reduce CO_2 to 0.05 Gt by 2050

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In brief

Decarbonizing China's passenger car sector would require both low-carbon behaviors and decarbonization technologies. Yet how behavioral changes and technological advancements can deliver optimized decarbonization effects throughout the life cycle remains underexplored. Chen et al. developed a novel integrated car fleet dynamic model and show that behavioral changes are important near-term decarbonization tools, while technological advancements are vital to long-term decarbonization. A combination of behavioral and technological measures can help China reduce CO_2 of passenger cars close to carbon neutrality (0.05 Gt) by 2050.

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Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions

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SCIENCE FOR SOCIETY Transportation plays a vital role in everyday life and is key to sustainable development. Transportation, however, also generates substantial CO_2 emissions and will account for 40% of global CO_2 emissions by 2030. Passenger cars account for almost half of all transport-related CO_2 emissions and are particularly problematic in China, the world's top passenger car consumer. The introduction of electric vehicles is often touted as a key solution to passenger car decarbonization. However, this technological fix does not account for emissions generated throughout the manufacturing and vehicle recycling process and relies on clean electricity supply during operation, which is unlikely to be available in the near term. It is therefore likely that driving habits will also need to change, i.e., driving less and opting to share mobility, but without additional guidance, policymakers can struggle to identify and implement the most optimal strategies. This analysis reveals that behavioral changes are by far the most optimal strategy in the short term, but long-term decarbonization and carbon-neutrality potential will primarily be driven by technological progress.

SUMMARY

The passenger car sector accounts for nearly half of all transport-related emissions. Rapid decarbonization is therefore important but challenging, particularly in China, where, despite recent emission peak (by 2030) and carbon-neutrality (by 2060) pledges, car ownership and associated emissions are increasing. Successful emissions reduction will require a rapid transition of both technology (e.g., toward electrification) and demand (e.g., driving less). However, how to successfully deploy these twin strategies for optimal outcomes remains unclear. Here, we develop an integrated fleet dynamics model that considers emissions associated with car manufacturing, operation, end-of-life recycling, and energy supply alongside socioeconomic changes. Our analyses reveal that optimal short-term results will be achieved through demand-oriented strategies, which can reduce emissions by 22% and achieve 2030 emissions peak targets. Technology-oriented strategies are more optimal when deployed in the longer term and can result in emission reductions of 91%. A successfully coordinated strategy could reduce China's passenger cars CO_2 emissions to 0.05 Gt by 2050.

INTRODUCTION

The transport sector is widely regarded as key to achieving the world's Sustainable Development Goals (SDGs).[1–4] For example, it contributes significantly to global greenhouse gas (GHG) emissions,[5] urban traffic congestion, and air pollution, and thus to at least three SDGs (SDG 3, SDG 11, and SDG 13).[6,7] Light-duty passenger vehicles or passenger cars (hereafter referred to as cars), as the primary mode of personal transport, contribute to 45% of global transport drive-cycle GHG emissions[8] (i.e., direct emissions in operation). This share could be even higher if the car-cycle emissions (i.e., indirect emissions in the upstream and downstream of the car life cycle like materials production, car manufacturing, and end-of-life management) and energy-cycle emissions (i.e., indirect emissions in the energy supply chain, particularly electricity generation) are considered.[9] Therefore, decarbonizing the global passenger transport sector would require a full life cycle (covering drive-cycle, car-cycle, and energy-cycle emissions) and system understanding (considering the fleet and technology dynamics) of the global and regional passenger car transition.[10,11]

This challenge is particularly relevant for China, the world's largest emitter that just put forward its ambitious dual carbon goals (i.e., peak by 2030 and neutrality by 2060[12]) in 2020. Passenger cars play an important role on its way toward carbon neutrality because they contribute to approximately 44% of the total emissions in the transport sector in 2017.[13] In fact, China has been the world's largest producer and consumer of cars over the past 10 years.[14] In the next several decades, China is expected to continue its motorization wave[15,16] because its current car ownership (129 cars per 1,000 people) is still comparably low (e.g., only 1/4 and 1/8, respectively, of the current level in Japan and the United States) (Figure S4). For example, the International Transport Forum Outlook[17] has estimated that one-sixth of the global passenger mobility increase will come from China. Such an increase will raise enormous challenges for China to achieve its climate ambition and thus requires effective strategies for emission mitigation.

Several strategies have been proposed, evaluated, and implemented to address the climate impact of car development in the past decades, which can be categorized largely into two transition pathways[18–20]: technology-oriented[21–27] and demand-oriented pathways.[28–31] Along the technology-oriented transition pathway, fuel economy improvement[32–34] has long been the most effective and widely discussed strategy. This can be achieved mainly by lightweight design (e.g., substituting standard steel with aluminum, magnesium, or carbon fiber) to reduce curb weight and thus the drive-cycle energy use and emissions,[35–41] or by powertrain technology innovation (e.g., electrification) to reduce the fossil fuel use and increase efficiency.[42–44] However, both lightweight and electrification would require new materials (e.g., wrought aluminum or lithium-ion batteries [LIBs]) and thus lead to emerging waste generation and increasing car-cycle emissions in material production and car manufacturing.[45–49] The increasing electrification may lead to extra energy-cycle emissions in electricity generation as well.[22,24] Therefore, their eventual climate gain depends on the trade-off between decreasing drive-cycle emissions and increasing car-cycle and energy-cycle emissions.[50–52] The demand-oriented transition pathway,[53] contrasting with the technology-oriented one, goes beyond technological improvement alone and involves discussion on downsizing the car fleet[54] and reducing associated energy use and emissions through alternative mobility patterns (e.g., sharing mobility,[17,55] on-demand mobility,[56] and ride sharing[18,57]) and green consumer behaviors[58] (e.g., smaller cars and less air-conditioning use). These strategies aim at ensuring the same mobility service without extra materials and emissions costs and are thus often argued as sustainable solutions with carbon benefits.[29,59]

How the material and climate benefits of such behavioral change solutions from demand-oriented transition are benchmarked with those from technology-oriented transition, however, remains poorly understood. Life-cycle assessment (LCA) is the most widely used tool in the literature to address such questions.[60–63] These LCA studies provide a whole life-cycle perspective for cars often on a functional unit basis to identify pivotal factors ranging from energy mix to production and recycling efficiency for mitigation strategies.[22,44,64,65] Nevertheless, it should be noticed that most LCA studies are static and thus cannot fully capture the temporal dynamics and interactions of the car fleet (stocks), technology development, and socioeconomic parameters,[23,45,62] except in a few studies.[21,47] A recent effort to address the trade-offs and synergies of different mitigation strategies is the Resource Efficiency and Climate Change (RECC) model framework that attempts to link the service (including cars), materials, and emissions.[66] Under this framework, the carbon emission reduction potentials from material efficiency strategies are quantified for residential building and car sectors on regional and global levels.[18] However, these results are based on aggregated scenarios (the Shared Socioeconomic Pathways). They have not yet considered the heterogeneous national context, detailed bottom-up data, and differences between technology- and demand-oriented pathways individually or in combination, especially for China.

Here we aim to address this gap by developing an integrated car fleet dynamics model that considers time-cohort-type dynamics (e.g., the changes of car ownership, car powertrain technology, and car segment over time) and material-energy-emission nexus (e.g., material demand, energy consumption, and full life-cycle emissions) and integrates demand- and technology-oriented parameters (see Figure 1 and Tables 1, 2, 3, and 4). Our model builds on China-specific bottom-up data and reveals the material and emission implications of China's future passenger car transition under various individual or combined technology- and demand-oriented transition scenarios. Results show that, in the short term, compared with technology-side mitigation potential (16%), demand-side mitigation strategies such as driving less, sharing cars, and lowering car

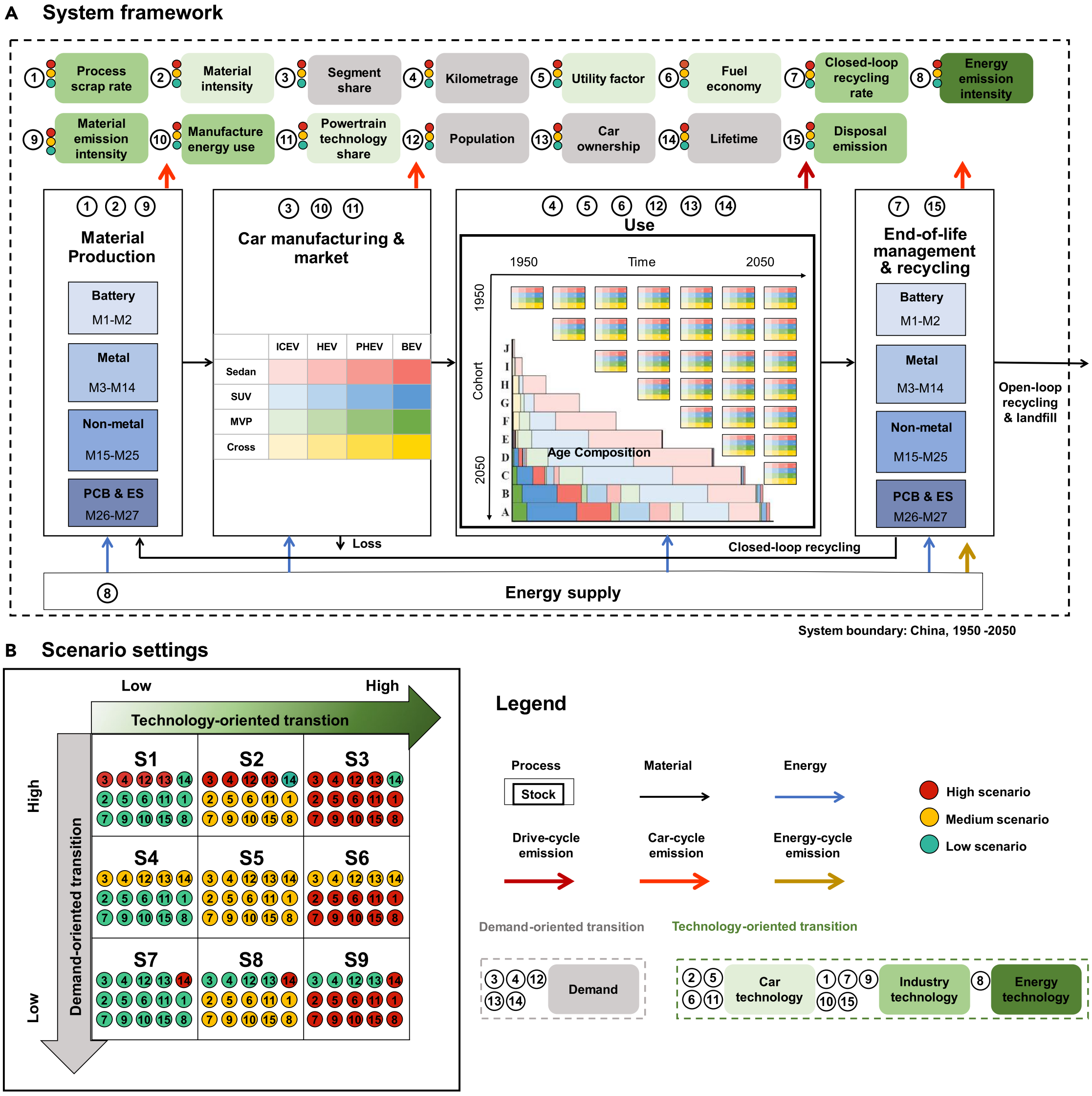

Figure 1. The integrated car fleet dynamics model framework and scenarios setting for material and climate implications of car transition

System framework (A) and scenario (B) settings. The car fleet is modeled in a time-cohort-type resolution (technology, segment, and material composition). M1–M27 denote the 27 types of material used in cars (detailed in Figure S2). A–J in the use phase exemplify the age structure of cars in a selected year. S1–S9 define the integrated scenarios (detailed in Table S5) with a combination of demand-oriented (detailed in Table 1 and the experimental procedures) and technology-oriented parameters (detailed in Table 2 and the experimental procedures). The numbers and signal lamp in front of the color-filled box indicate the type of parameter and their future scenario development, respectively, considered in this case study. Drive-cycle emission, car-cycle emission, and energy-cycle emission include only carbon emissions. BEV, battery electric vehicle; Cross, crossover; HEV, hybrid electric vehicle; ICEV, internal combustion engine vehicle; MPV, multiple-purpose vehicle; PCB&ES, printed circuit boards and electrics; PHEV, plug-in hybrid electric vehicle; SUV, sport utility vehicle.

ownership can enable a greater CO_2 reduction (22%) and help China's passenger car sector reach CO_2 emissions peak before 2030. However, in the long term, the decarbonization potential of demand-side strategies will be limited to only 5%, whereas technology-side mitigation strategies such as better fuel efficiency, decarbonization of the power grids, and manufacturing/recycling process, especially car electrification, can drastically curb long-run total emissions by 91% in 2050. A coordination of the demand-side and technological-side mitigation strategies could help China's passenger car sector reach close to a carbon neutrality (i.e., 0.05 Gt CO_2) by 2050. Our results on the carbon emission pathways and reduction potentials of China's car sector would help inform tailored mitigation strategies and identify maximum combined effects of demand-side strategies and technological approaches.

RESULTS

Scenario settings for transition pathways

To explore China's future car fleet dynamics and implications on materials and climate, we defined low, medium, and high levels for demand-oriented transition pathways (shown as rows in

Table 1. Overview of demand-oriented scenario narratives and parameter assumptions

Scenario	S1	S2	S3	S4	S5	S6	S7	S8	S9
Demand-oriented scenario narrative	high demand: the demand will continue to grow with increasing population, high car ownership, car-dominant mobility, high scrappage rate, and preference for SUV			medium demand: the demand will gradually slow down with decreasing population, lower car ownership, and less car use based on green lifestyles, while scrappage rate and segment preference remain the same			low demand: we enter a low-demand society with a further decreasing population and lower car ownership and car mobility activity because of sharing mobility and green lifestyles, and people tend to scrap cars less frequently and tend to buy smaller size cars		
Parameters	S1	S2	S3	S4	S5	S6	S7	S8	S9
Population	gradually reach 1.5 billion by 2050			gradually reach 1.4 billion by 2050			gradually reach 1.3 billion by 2050		
Ownership	gradually reach 480 cars/1,000 people by 2050			gradually reach 390 cars/1,000 people by 2050			gradually reach 300 cars/1,000 people by 2050		
Lifetime	gradually reach 10.5 years by 2050			remain 13.2 years			gradually reach 16.1 years by 2050		
Kilometrage	gradually reach 14,775 km/year by 2050			gradually reach 13,280 km/year by 2050			gradually reach 11,804 km/year by 2050		
Segment share	the segment share of SUVs and MPVs gradually reaches 60% and 20%, respectively, by 2050			the segment share of sedans and SUVs gradually reaches 51% and 42%, respectively, by 2050			the segment share of sedans gradually reaches 84% by 2050		

Figure 1 and Table 1; represented by five types of parameters) and technology-oriented transition pathway (shown as columns in Figure 1 and Table 2; represented by 10 types of parameters). Nine combined scenarios based on these 15 types of parameters (S1–S9 in Figure 1B and detailed in Table S5) were used to present the results with a wide spectrum (including the possible worst and best situations). Details and further elaboration of the 15 types of parameters and the nine combined scenarios can be found in the experimental procedures and supplemental information. We considered five types of key parameters for the demand-related transition (population, ownership, lifetime, kilometrage, and segment market share) to determine the level and use of car fleet. The low, medium, and high levels of these five parameters are based mainly on their historical patterns in China and future projections considering different socioeconomic development narratives. We consequently determined the high-demand (S1–S3), medium-demand (S4–S6), and high-demand (S7–S9) transitions as shown in Table 1.

The 10 types of technology-oriented parameters were further categorized into car-technology-related, industry-technology-related, and energy-technology-related parameters (as shown in green dashed box in Figure 1). For all 10 types of technology-oriented parameters, the low levels were assumed to remain the same as the level in 2018; the medium levels were based largely on China's country-specific policy framework and technology roadmaps, e.g., Technology Roadmap for Energy Saving and New Energy Vehicles[88] and China's energy and power system development under its "dual carbon" goals;[84] and the high levels were assumed accordingly based on the medium scenarios or literature.[85–87] We consequently conceptualized the low-technology (S1, S4, and S7), medium-technology (S2, S5, and S8), and high-technology (S3, S6, and S9) transitions as shown in Table 2.

Materials demand and secondary materials provision

Figure 2 shows, under the nine combined scenarios (S1–S9 in Figure 1B), the impact of demand- and technology-oriented transitions on the material gross demand and potential secondary material provision. Observing vertically in each column when the technology-oriented parameters do not change, we found that the demand-oriented transition has significant impacts on the gross material demand and potential secondary materials provision (Figures S31–S57). Compared with S1 (high demand), S4 (medium demand) and S7 (low demand) will reduce 942 Mt (or 29%) and 1,734 Mt (or 54%) of cumulative material gross demand between 2019 and 2050. When S4 (medium demand without technological improvement) was used as a reference, lower car ownership and longer car lifetime, respectively, can reduce materials demand for new cars, resulting in 23% (514 Mt) and 6% (133 Mt) reduction of all materials gross demand from 2019 to 2050 (see Figure S59). Meanwhile, the popularization of larger-size sport utility vehicles (SUVs) and multiple-purpose vehicles (MPVs), which can indeed be seen as an emerging trend in China, will require an extra 45 Mt of materials (mainly in the form of regular steel and high-strength steel [HSS]) (see Figure S59).

Car-technology-oriented transition, on the contrary, will affect the gross material demand to a lesser extent (as shown horizontally in each row in Figures 2 and S32–S58). Ambitious technology development (S3, S6, and S9) will only lead to 657, 501, and 364 Mt of gross material demand reduction compared with the low- (S7), medium- (S4), and high-demand (S1) scenarios, respectively. It is interesting to notice that these ambitious technology scenarios (S3, S6, S9) will bring in more reduction in regular steel gross demand (by 1,104, 749, and 468 Mt), and thus lead to an oversupply of regular steel scrap after 2030 (Figure S33).

Table 2. Overview of technology-oriented scenario narratives and parameter assumptions

Scenario	S1	S4	S7	S2	S5	S8	S3	S6	S9
Technology-oriented scenario narrative	low technology: all technology-oriented parameters will remain the same as the 2018 level without any further improvement			medium technology: the future car fleet will follow China's policy plan in fuel economy improvement, electrification, and lightweight; the car industry will gradually improve its energy and resource efficiency; and the energy system will continue its renewable energy development			high technology: the future car fleet will undergo even more ambitious fuel economy improvement, electrification, and HSS-intensive lightweight; the car industry will quickly employ energy and resource efficiency strategies; and the energy system will have the highest share of renewable energy		
Parameters	S1	S4	S7	S2	S5	S8	S3	S6	S9
Fuel economy	remain the same as the 2018 level			gradually reach a 30% reduction by 2050			gradually reach a 50% reduction by 2050		
Powertrain technology share	ICEVs keep dominating the market (91% by 2050)			BEVs gradually dominate the market (77% by 2050)			BEVs and PHEVs quickly dominate the market (100% by 2035)		
Utility factor	gradually reach 0.82 by 2050			gradually reach 0.89 by 2050			gradually reach 0.94 by 2050		
Material intensity	remain the same as the 2018 level			diverse lightweight deployment with HSS, aluminum, magnesium, and carbon fiber			HSS intensive lightweight deployment		
Process scrap rate	remain the same as the 2018 level			gradually reach a 30% reduction by 2050			gradually reach a 70% reduction by 2050		
Closed-loop recycling rate	0% for all materials			gradually reach 70% for metals and 50% for non-metals by 2050			gradually reach 100% for metals and 70% for non-metals by 2050		
Material emission intensity	remain the same as the 2018 level			medium-level reduction paced with high share (81% by 2050) of low-carbon electricity			ambitious reduction paced with extremely high share (92% by 2050) of low-carbon electricity		
Manufacture energy use	remain the same as the 2018 level			gradually reach a 30% reduction by 2050			gradually reach a 50% reduction by 2050		
Disposal emission	remain the same as the 2018 level			gradually reach a 30% reduction by 2050			gradually reach a 50% reduction by 2050		
Energy emission intensity	remain the same as the 2018 level			non-fossil fuel mix in electricity production gradually reaches 81% by 2050			non-fossil fuel mix in electricity production gradually reaches 92% by 2050		

However, such technology-oriented transition strategies (especially the lightweight and electrification) will result in a significant increase in lightweight materials and LIB materials (see Figure S58). For example, the lightweight strategy would lead to a dramatic increase in lightweight materials demand, including HSS, wrought aluminum, cast aluminum, magnesium, and carbon fiber, most of which are carbon intensive when produced in China currently. The LIB demand is only 1.0, 0.6, and 0.3 Mt, respectively, in 2050 for scenarios S1, S4, and S7 with assumed no technology change (Figure S31). For the medium demand scenario (S4), further car electrification to medium (S5) and high (S6) levels, however, will increase the LIB gross demand (and consequently the embodied critical battery materials such as lithium, cobalt, graphite, and nickel) by a factor of 18 and 22, respectively, in 2050. The cumulative gross demand for LIB from 2019 to 2050 in high-technology scenarios (S3, S6, and S9) will reach 472, 303, and 174 Mt, which are 15, 14, and 13 times higher than that of low-technology scenarios (S1, S4, and S7), respectively. However, such ambitious electric cars deployment will relieve the demand for platinum (Figure S44), which is used both in the exhaust pipes of traditional internal combustion engine cars and in future fuel cell cars.[89] Such trade-offs are important for securing materials supply for future car transition because both battery materials (e.g., cobalt and lithium) and platinum are considered critical materials that may face future geopolitical supply risks.[90–92]

In addition to potential supply constraints, the increasing demand for those emerging materials (especially for LIBs and carbon fiber) in cars will lead to both challenges (for waste management) and opportunities (for recycling and reuse) at the end of life. For example, realizing 100% car electrification in 2035 in the ambitious technology scenario (S6) will result in a

Table 3. Description of demand-oriented parameters

Key parameters	Descriptions	Detailed explanation and assumptions in the supplemental information
Population	China's population will reach 1.3, 1.4, and 1.5 billion in 2050 for the low, medium, and high scenarios based on United Nations population forecast.[67]	Figure S3
Car ownership	the car ownership is assumed to gradually increase to 300, 390, and 480 units per 1,000 people in 2050 for the low, medium, and high scenarios, respectively, which is similar to the current car ownership level in Russia, Slovakia, and Japan, respectively	Figure S4
Lifetime	the medium car lifetime is obtained from the literature;[68] the low and high lifetime values are considered as a result of behavior change	Figure S5
Segment share	the medium segment share is based on the current situation with 42% in SUV (the world's highest), the low segment share is assumed based on that people gradually abandon bigger-sized cars and go back to sedan, and the high segment share is assumed based on that people will prefer bigger vehicles with an even higher share in SUVs (60%) and MPVs (20%) in 2050	Figure S6
Kilometrage	the annual kilometrage for a new car for the low and medium scenarios is 20% and 10% lower than that in the high scenario (14,755 km) because of mode shift to public transit and cycling; the final kilometrage for different types of car is determined by the annual kilometrage and use intensity	Figures S7 and S21

skyrocketing growth of retired LIBs from 158 tons in 2018 to 12.58 Mt in 2050 (Figure S31). LIBs retired from cars with over 80% remaining capacity can be easily reused for energy storage;[48] therefore, if properly managed, such booming end-of-life LIBs may provide an enormous opportunity for cascading reuse in the energy storage sector. Recycling those LIBs can relieve the dramatic demand for primary LIB materials as well; for example, the cumulative demand for primary LIBs in S6 will be 24% lower than the cumulative LIB gross demand in S6 with further material efficiency improvement in car manufacturing and waste management. Similar to LIBs, the primary demand for most bulk materials would be lowered as well with increasing closed-loop recycling rate and decreasing process scrap rate (Figure S60). However, secondary materials supply alone still cannot satisfy the increasing material gross demand in the medium and long term largely because of China's relatively young car fleet and the technology shift.

Emission pathways in demand and technology scenarios

The emission pathways under the nine combined scenarios in Figure 3A reveal that both demand-oriented and technology-oriented transition parameters have significant and varying impacts on emission reduction potentials up to 2050. The annual total emissions in S1, as the most emission-intensive transition with high demand and low technology (assumed the same as the 2018 level), have almost tripled from 2019 (0.8 Gt) to 2050 (2.0 Gt). Using S1 as a benchmark, the demand-oriented transition (e.g., as shown in the columns S1, S4, and S7 in Figure 3A) can significantly reduce annual total emissions in the short term. The technology-oriented transition (e.g., as shown in rows in Figures 3A and S70), on the contrary, will increase annual total emissions slightly in the short term (e.g., because of the initial introduction of new technologies) but reduce annual emissions more in the long run (e.g., with climate gains from technology development).

The structural change can further explain the change of annual total emissions among drive-cycle, car-cycle, and energy-cycle emissions from 2019 to 2050 in different scenarios. When S3 (high demand, high technology) and S7 (low demand, low technology) are compared, for example, it can be seen that car-cycle- and energy-cycle-induced emissions in S3 are almost always higher than that in S7 (Figures S71 and S73), whereas its drive-cycle emissions decrease dramatically and are lower than that in S7 after 2030 (Figure S72). Similar trade-offs among the three categories of emissions exist when other technology-oriented and demand-oriented scenarios are compared. This essentially reveals the carbon payback time when the benefits of drive-cycle emissions reduction (e.g., with greener car fleets and energy mix) exceed the costs of car-cycle (e.g., because of powertrain technology innovations and lightweight strategies) and energy-cycle (e.g., more electricity-induced emissions in the energy supply chain) emissions increase.[93]

When it comes to cumulative total emissions from 2019 to 2050, the demand-oriented and technology-oriented transitions show similar potentials but different patterns in emissions reduction. The demand-oriented transition can halve the 2019–2050 cumulative emissions (e.g., 55, 40, and 26 Gt, respectively, for S1, S4, and S7). Its effect on car stock and use mitigates drive-cycle emissions, which cumulatively account for the largest share of the total emissions, e.g., 61%, 61%, and 61%, respectively, in S1, S4, and S7. The technology-oriented transition, similarly, can halve the cumulative total emissions of corresponding demand scenarios as a result of technology innovation, diffusion, and efficiency improvement (e.g., reduction by 55%, 52%, and 50%, respectively, from 55, 40, and 26 Gt in S1, S4, and S7 to 25, 19, and 13 Gt in S3, S6, and S9). It should be noted that, even in a technology-oriented transition, drive-cycle

Table 4. Description of technology-oriented parameters

Category	Key parameter	Description	Detailed explanation and assumptions
Car technology related	fuel economy	the fuel economy in 2050 for the medium and high scenario will be 30% and 50% lower than the level in 2018	Figures S18 and S19
	material intensity	in total, 27 types of material are considered in material composition to reflect a lightweight strategy; the material intensity for the low, medium, and high scenarios, respectively, is based on the situation in 2018, China's 2020 Car Technology Roadmap, and steel-intensive lightweight strategy	Figures S10 and S11 and Table S4
	powertrain technology share	the medium scenario presents slow electrification and fast energy-saving transition that ICEVs will be phased out in 2035 with EVs and HEVs accounting for 45% and 55%, respectively; the high scenario is based on that ICEVs and HEVs will be phased out in 2035	Figure S8
	utility factor	the utility factor indicates the percentage of distance traveled on charge-depleting mode; the value is assumed to be 0.82, 0.89, and 0.94, respectively, in 2050 for the low, medium, and high scenarios	Figure S9
Industry technology related	material emission intensity	the emission intensity for both primary and secondary production of the 27 types of material is mainly based on China Automotive Life Cycle Assessment Model (CALCM)[69] and Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET)[70]	Figures S14 and S15
	manufacture energy use	the car manufacturing energy use includes stamping, welding, coating, assembly, and power station house.; the manufacturing energy use is assumed to be 30% and 50% lower in 2050 than the current level for the medium and high scenarios	Figure S16
	process scrap rate	the process scrap generation rate of the 27 types of material was considered individually; the low scenario values were assumed as the level in 2018 derived from multiple resources;[39,52,71–75] the values in 2050 are assumed to be 30% and 70% lower than the value in 2018 for the medium and high scenarios	Figure S13
	closed-loop recycling rate	this current closed-loop material recycling rate from scrapped cars was compiled from multiple resources;[39,52,71–83] the metal and non-metal recycling rates into the car sector, respectively, are assumed as 0% and 0% (for the low scenario), 70% and 50% (for the medium scenario), and 100% and 70% (for the high scenario)	Figure S12
	disposal emission	the disposal emission is based on the literature[47] because of missing China-specific information; the medium and high scenario values in 2050 are assumed to be 30% and 50% lower than the current value because of, e.g., energy-saving technology introduction	Figure S17
Energy technology related	energy emission intensity	the non-fossil fuel mix in electricity production is assumed to reach 81% and 91% in 2050, respectively, for the medium and high scenario based on the literature,[84–86] resulting in an electricity emission intensity of 0.22 and 0.09 kg CO_2/kWh;[84–86] the gasoline and natural gas emission intensity is assumed to be 25% and 50% lower, respectively, than the current value based on the literature[87] in the medium and high scenarios	Figure S20

emissions still make up the largest share (e.g., 41% in S3) in the cumulative total emissions from 2019 to 2050. But the annual share of drive-cycle emissions in S3 will decrease dramatically, for example, by 54%, 49%, 16%, and 1%, respectively, in 2020, 2030, 2040, and 2050.

Interestingly, the cumulative total emissions of S3 (25 Gt) and S7 (26 Gt) are close to each other, indicating that emission mitigation could be realized equally through either demand-oriented or technology-oriented transition. However, demand-oriented mitigation (i.e., lower car ownership, less kilometrage, longer lifetime, and smaller cars) is the most direct and effective in the short term. After this window of opportunity, technology-oriented mitigation (e.g., car electrification and fuel economy improvement) will play a more important role. Moreover, the structural distributions among drive-cycle, car-cycle, and energy-cycle emissions along the demand- and technology-oriented transition pathways are different (e.g., less drive-cycle emissions both cumulatively and annually in a demand-oriented transition), which is important for climate policy and responsibility allocation with a sectoral approach.

Climate change mitigation potentials

Faced with the pressing climate change challenge, mitigation strategies along both demand- and technology-oriented transition pathways will, in practice, be used in combination in one way or another. We used S4 (medium demand with current technology) as a benchmark and conducted a sensitivity analysis to explore the effect of various partially combined, as well as fully and sequentially integrated, strategies on emission pathways (both total and drive-cycle, car-cycle, and energy-cycle emissions as shown in Figure 4). Under such a medium-demand scenario, the technology-oriented strategies will bend the emission pathways with a peak around 2027–2028 (Figures 4A–4E). The individual contribution of fuel economy improvement, electrification, lightweight, energy decarbonization, and industry decarbonization to cumulative emission reduction from 2019 to 2050 is 7.9, 5.1, 4.1, 3.6, and 3.7 Gt, respectively (Figure S87).

When all these technology-related strategies are implemented in sequential combination (ordered by conceived feasibility as shown in Figure 4G), the annual total emissions will peak at 1.0 Gt in 2024 (14 years earlier than S4). In that year, drive-cycle emissions still contribute to over half (55%) because traditional internal combustion engine vehicles (ICEVs) still account for 78% of total car stocks and provide 73% of mobility service (Figure S22). Later, as those technologies gradually take effect, the annual total emissions will decrease quickly to 0.1 Gt in 2050 (only 17% of the 2018 level). If ambitious demand mitigation is further added, which is the most extreme scenario (as in S9 in Figure 3 and shown in Figure 4G), the annual total emissions will peak at 0.8 Gt in 2022 (3 years earlier than the fully integrated technology scenario) already and rapidly decrease to 0.05 Gt in 2050. The ultimate 2019–2050 cumulative emissions after considering all these reduction wedges (technology improvement and demand mitigation) are 13.2 Gt (Figure 3B).

Figure 4 confirms the changing contributions of technology- and demand-oriented strategies over time and thus changing mitigation priorities as well. For example, in 2025, the emission mitigation contribution of the combined demand-oriented strategies is 22% (of total emissions in that year), while that of the combined technology-oriented strategies is only 16% (see Figures 4G and S88). When ambitious technology strategies are gradually implemented by 2050, the emission reduction contribution of the combined demand-oriented strategies will reduce to only 5% (of total emissions in that year), while that of the combined technology-oriented strategies will rise to 91% (see Figures 4G and S88).

It is important to point out that some mitigation effects of the above-mentioned technology- and demand-oriented strategies may cancel each other out when implemented in combination, so sequence and pace of implementation matter for aggregated mitigation potentials. For example, the total emissions in combined medium car technology (medium fuel economy, medium electrification, and medium lightweight) are higher than S4 (without any technological improvement) before 2027 if the present electricity mix and LIBs production technologies were assumed to be unchanged (Figure S74). This suggests that radical electrification alone could lead to extra negative environmental impact if the industry-related and energy-related technologies did not progress at the proper pace. China's current electricity mix is still coal dominated with high emission intensity,[95] and the present LIBs are still heavy in weight and emission intensive in production. Therefore, the lightweight of the entire car (both body and battery), further industry decarbonization, and further energy decarbonization[96] in parallel are critical for achieving more climate gains of car fleet electrification.

DISCUSSION

Our results clearly demonstrate the necessity and usefulness of a system approach that considers time-cohort dynamics and the material-energy-emission nexus to realize the best-combined effect in material and emission reduction associated with China's car transition in the next decades. Such a systematic overview helps maximize synergies and avoid trade-offs among drive-cycle, car-cycle, and energy-cycle carbon emissions and between climate change mitigation and other sustainability challenges. It can also inform the policymakers and industry decision-makers on the timing and effectiveness of various strategies at hand to curb the whole-life-cycle emissions of cars.

When all drive-cycle, car-cycle, and energy-cycle carbon emissions are considered, our explorative scenarios show that the annual total emissions associated with China's car transition could peak before 2030 (the target year when China's national emissions are set to peak[12]) in most transition pathways. With various technology-oriented and demand-oriented strategies implemented, the annual total emissions can peak between 2022 and 2025(as shown in Figure 4G) and be significantly reduced after the peak. However, even with a combination of all strategies, emissions (including drive-, energy-, and car-cycle emissions) in 2050 will remain at 0.05 Gt (just 47% less than in 2005), a reduction that is smaller than China's 90% reduction target for the whole economy.[97]

Car-related technology progress alone (without progress in the industry- and energy-related technology) can help lower drive-cycle emissions (Figure S77) and thus total emissions (Figure S74) dramatically in the long run; however, they will increase car-cycle (Figure S75) and energy-cycle (Figure S76) emissions in the short term. The main reason for the short-term emission increase lies in the emission-intensive LIB and lightweight materials production with the current coal-based electricity mix and low closed-loop recycling rate (Figure S67). Thus, the pace and sequence of battery and renewable energy technology development and penetration would be critical to maximize total climate gains (Figures S75 and S76). For example, before China's energy sector can be significantly decarbonized with a higher share of renewable energy, LIBs lightweight should be explored by battery manufacturers. HSS may be a better choice

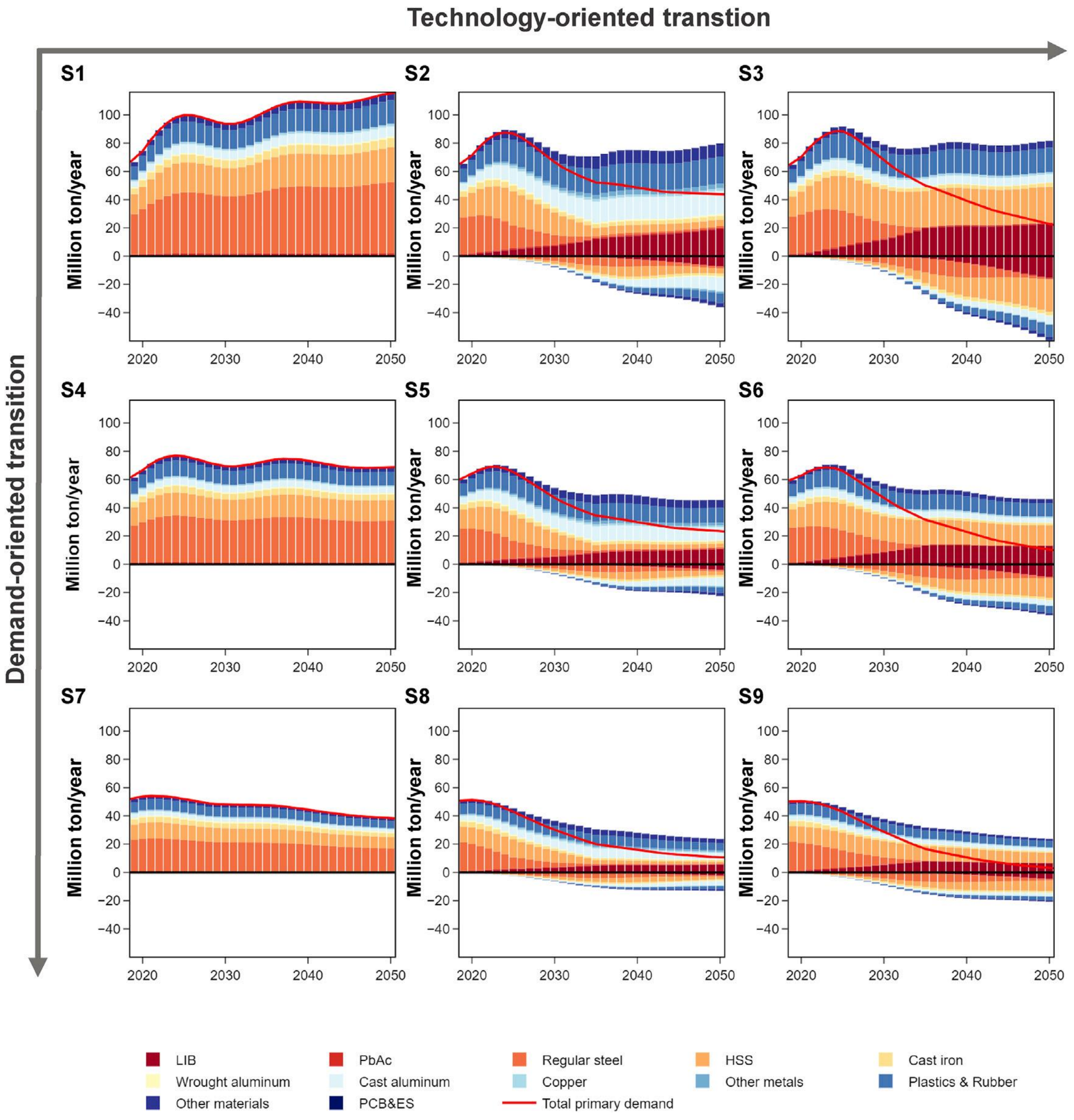

Figure 2. Materials demand due to new cars deployment and potential secondary material provision from scrapped cars from 2019 to 2050 in China for the nine combined scenarios

Positive values in stacked bar chart are for gross demand by materials; solid red lines indicate annual total primary materials demand; and negative values in the stacked bar chart are for potential secondary material provision from closed-loop recycling of scrapped cars. HSS, high-strength steel; LIB, lithium-ion battery; PbAc, lead-acid battery; PCB&ES, printed circuit boards and electrics. Details of nine combined scenarios (S1–S9) can be found in Tables 1 and 2.

than electricity-intensive aluminum and carbon fiber in car body lightweight under the current energy mix (Figure S67). Improving material closed-loop recycling rates in car production with proper industry guidelines and best practices will further reduce energy consumption, as well as car-cycle emissions, before the energy decarbonization (Figure S75).

Such increase of energy-cycle emissions caused by car technology strategies (especially electrification) under China's present energy mix reaffirms the importance of energy decarbonization (e.g., via appropriate subsides,[98] market mechanisms, and innovation support) in reducing the energy-cycle emissions and thus low-carbon transition of the car sector (Figure S76). This would be particularly critical before the fast deployment of car electrification. However, this may compete with clean energy demand in the low-carbon transition of other sectors (e.g., building and food) in the same window of opportunity and thus end up with a zero-sum game.[99] Therefore, a system plan and good timeline by policymakers and industry decision-makers are important to realize the best-combined effect in emission reduction.[100] Effective climate policy should adequately consider the trade-offs not only among different emission sources of one sector (e.g., drive-cycle, car-cycle, and energy-cycle emissions in different car transition pathways), but also across different sectors (e.g., building, transport, and

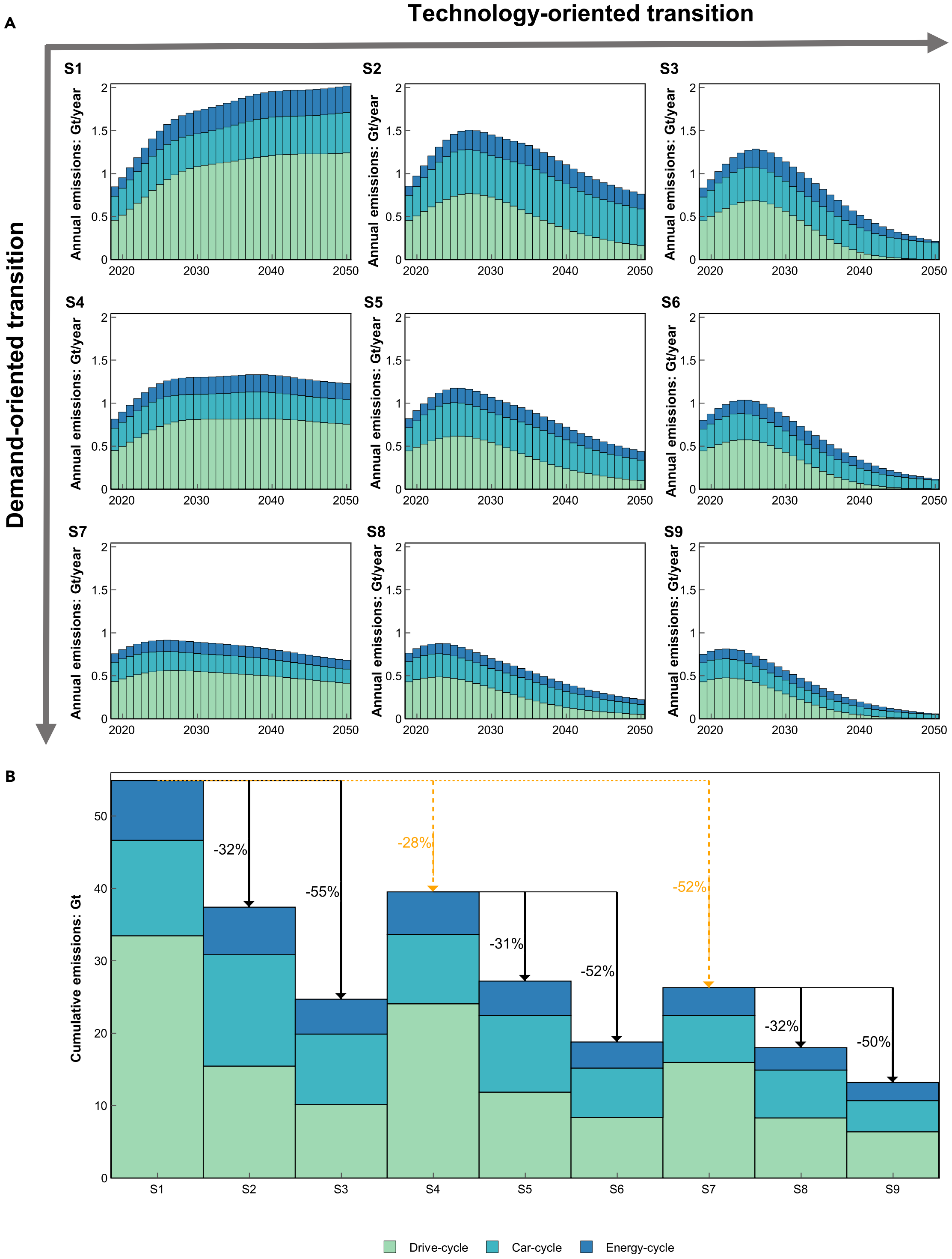

Figure 3. Carbon emission pathways associated with China's car transition up to 2050 in the nine combined scenarios

Annual (A) and cumulative (B) total emissions. Black solid arrows indicate the emission mitigation potential (number in black beside the arrow) under the medium- and high-technology-oriented transition for the low-demand (S7), medium-demand (S4), and high-demand (S1) scenarios. Orange dashed arrows indicate the emission mitigation potential (number in orange beside the arrow) from the high-demand scenario (S1) to the medium- (S4) and low-demand (S7) scenarios. Details of nine combined scenarios (S1–S9) could be found in Tables 1 and 2.

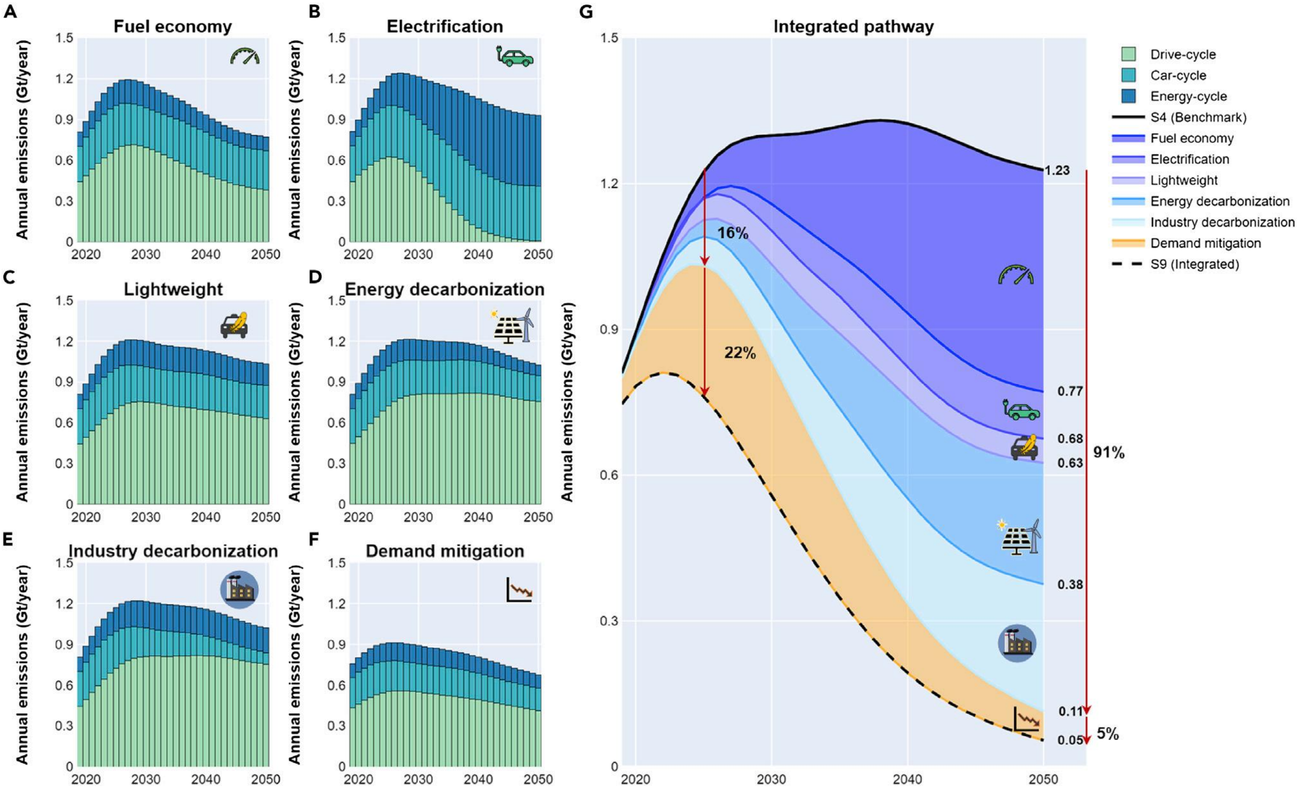

Figure 4. The carbon emission pathways under various partially and fully combined strategies, benchmarked to a medium-demand-with-current-technology transition (S4)

(A–F) Six single or partially combined strategies, respectively: (A) fuel economy improvement, (B) electrification with high utility factor, (C) lightweight, (D) energy decarbonization, (E) industry decarbonization, and (F) demand mitigation (from medium demand to low demand).

(G) Emissions reduction wedges[94] with combined technology and demand-oriented strategies that are sequentially ordered by conceived feasibility (more feasible ones go first).

food),[99] for maximized reduction and tailored regulation for different sectors.

The significant amount of materials demand (particularly LIBs) and skyrocketing waste growth (Figure S31) at the end of life in the future car transition should not be overlooked as well, to avoid a problem shift among sustainability challenges from climate to resource and waste. For example, the potential oversupply of regular steel because of car lightweight (Figure S33) and implications on the whole steel cycle deserve special attention. Cascading recycling of car steel in the construction sector may absorb a big portion of such oversupply from car transition; however, this may alter the steel cycle and lower primary steel demand, thus challenging the planning of steel production capacity. Furthermore, the booming LIBs retired from cars with over 80% remaining capacity is promising for cascading use in the energy storage systems,[48] which provides more opportunities for energy saving and emission reduction than substituting primary battery materials demand alone.[101] Therefore, the materials cycles (both bulk and critical) associated with the car transition should be better understood to achieve win-win-win among relevant resource, waste, and climate policies.

Compared with technology-oriented strategies, demand-oriented strategies play a significant role in emission reduction in the short term (see Figures 4G and S88). So policy should be in place urgently to capture this window of opportunity, before car-, energy-, and industry-related technologies become mature or penetrate the market for larger gains in the future. Some megacities in China (e.g., Beijing) have already introduced a license plate lottery policy to restrain rapid car registration.[102] Other examples along this line include raising the car purchase tax[103] (especially for bigger cars and SUVs, as seen momentarily in China) and gasoline price.

More importantly, crafting further demand-oriented policies to effectively reduce travel and car mobility demand would be essential in curbing total emissions.[104] First, car-sharing, on-demand mobility, or ride hailing with fewer car kilometers or even fewer car stocks to provide the same passenger mobility service should be encouraged.[105] Second, nudging short- and medium-distance travel modal shift toward low emission mobility (e.g., public transport, cycling, and walking) through the effort of companies (e.g., sharing bike operators)[106,107] and infrastructure investment and development[108] would be necessary. Third, compact and smart-built environment development (e.g., denser neighborhoods) could reduce car use in the long term,[109,110] ease accessibility, and increase active mobility (e.g., walking and cycling). Considering China's further urbanization ambition in the next decade, particularly in the yet-to-develop cities in western China, such spatial planning issues deserve timely and special attention from urban policymakers.

Achieving such demand-oriented mitigation potentials in practice would be complex and challenging, because this requires joint efforts from policymakers at different levels of government, industry, and consumers. This is, however, a must in parallel to all technology-oriented strategies, if we want to maximize carbon emissions reduction or achieve our carbon-neutrality ambition in the future car transition. Actually, in addition to the five types of demand-oriented parameters we considered in this analysis, more strategies may be explored on the demand side and deserve more profound and quantitative investigation in the future. For example, how much could car ownership be reduced through new sharing mobility patterns? What kinds of nudging policy and how much infrastructure investment would be needed to enable a modal shift from car to public transport or active mobility? How can we evaluate the substantial co-benefits[27,93] on air quality, health, and traffic congestion when optimizing urban built environment and thus reducing car mobility and increasing active mobility? As our study demonstrated here for China, all these require a systematic approach that integrates different sub-systems and considers trade-offs among different sectors and targets.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the lead contact, Gang Liu (gli@igt.sdu.dk and geoliugang@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

Dynamic car, material, and emissions data are deposited in the Zenodo repository: http://doi.org/10.5281/zenodo.6812245. The bottom-up car and material data are not publicly available as part of the data that are licensed, but they are available from the lead contact on reasonable request. The core python code of the dynamic model is available on GitHub: https://github.com/IndEcol/ODYM. Custom code for this study is available from the corresponding author on reasonable request.

Integrated model framework and module description

We developed an integrated car fleet dynamics model to depict and simulate the fleet dynamics of cars and implications on linked material, energy, and emission layers, parameterized along both demand-oriented and technology-oriented transition pathways. This integrated model consists of three key modules on fleet dynamics, embodied materials cycle, and consequent GHG emissions. More details on the model framework can be found in the supplemental experimental procedures.

The fleet dynamics module, at the core of the integrated model, simulates car stocks and flows retrospectively (1950–2018) and prospectively (2019–2050). This module has a high resolution for cars that specifies not only powertrain technologies (i.e., ICEV, hybrid electric vehicle [HEV], plug-in HEV [PHEV], and battery electric vehicle [BEV], as often seen in the literature[39,47,65]) but also segments (i.e., sedan, MPV, and SUV, and crossover), shown as a four-by-four matrix in the car manufacturing and market process in Figure 1. Such a high resolution could help depict the historical dynamics of the car fleet more accurately and enable consideration of consumer preference factors such as the popularization of SUVs in China (Figure S6). Various data sources and classification (see Tables S1–S3) are compiled and consolidated for this purpose, including stock data from national statistics,[111] sales data from China Association of Automobile Manufacturers (CAAM),[112] and industry data from China Automotive Technology and Research Center (CATARC)[69] (Figure S1).

The associated material module, which builds on the fleet dynamics module and materials intensity and the mass balance principle, simulates materials gross demand, secondary materials provision, and primary material net demand (subtracting potential secondary supply from materials gross demand). We have considered 27 types of material, including two battery materials, LIB and lead-acid battery (PbAc), 12 metals (regular steel, HSS, cast iron, wrought aluminum, cast aluminum, magnesium, titanium, copper, zinc, nickel, lead, and platinum), 11 non-metallic materials (thermoplastics, thermoplastic elastomers, duromers, rubber, textiles, lacquers, adhesives, underseal, modified organic natural materials, ceramics, and carbon fiber), and PCB&ES (printed circuit boards and electrics) in our model (see Figures 1 and S2). For simplification in presentation, we further grouped the seven types of metal other than steel and aluminum as "other metals," three types of plastic and rubber as "plastic & rubber," and the other six types of non-metallic material as "other materials" (Figure S2). Finally, 12 categories of materials were presented in our results, such as in Figure 2.

Our emissions module considered the whole life cycle of cars from materials production to car manufacturing, use phase, and end-of-life car management and recycling, as well as the linked energy supply chain (e.g., electricity, gasoline, and natural gas). The consequent emissions can be categorized into three types: drive-cycle emissions (direct emissions from use phase), car-cycle emissions (indirect emissions from the upstream materials production and car manufacturing and downstream end-of-life management and recycling), and energy-cycle emissions (indirect emissions from the energy supply chain).

Parameters assumption and scenarios setting

Our integrated car fleet dynamics model can be parameterized from various socioeconomic, technological, and policy aspects. We defined 15 types of key parameters in this analysis, as detailed in Tables 3 and 4, and further categorized them along both demand-oriented (5 types of parameters reflecting the level and use of car fleet) and technology-oriented (10 types of parameters reflecting various technology roadmap pathways; further categorized as car-, industry-, and energy-related technologies) transition pathways of car fleets. For example, in a demand-oriented transition, population, and car ownership reflect the mobility service represented by total car stock; the lifetime of cars determine the physical car stocks and flows; the segment share indicates consumer preferences on size and style; and the kilometrage (combining annual driving distance and use intensity) reflects the use patterns of cars. Similarly, car-related technologies, fuel economy improvement, lightweight strategy (material intensity), and diffusion of low-carbon powertrain technologies (e.g., HEV, PHEV, and BEV) are important parameters. Details of specific assumptions can be found in Tables 3 and 4 and the supplemental information.

The low scenario of these 10 technology-related parameters was assumed to remain at a constant level as in 2018. Their medium scenario is determined based as much as possible on China-specific sources: (1) for the car-related technologies (material intensity, utility factor, fuel economy, and powertrain technology share for parameters 2, 5, 6, and 11, respectively, as shown in Figure 1), China's Car Technology Roadmap published in 2020[88] and literature values[21,39,47] were used; (2) for industry-technology related parameters (process scrap rate, closed-loop recycling rate, material emission intensity, manufacture energy use, disposal emission for parameters 1, 7, 9, 10, and 15, respectively, as shown in Figure 1), industry expert consultation and literature values[52,66,113–115] were used; and (3) for the energy-related technologies (energy emission intensity for parameter 8 as shown in Figure 1), China's Energy Outlook[84] and literature[87] were used for future supply chain emission intensity of energy (electricity, gasoline, and natural gas). The high scenario of these 10 technology-related parameters is assumed accordingly (comparably more ambitious) based on the medium scenario values and literature.[85,87]

In theory, combining the high, medium, and low values of each parameter could result in over 10 million combinations and scenario results. To simplify this and provide an overarching range for material and emission implications of car transition, we have conceptualized three demand narrative scenarios (Table 1) and three technology narrative scenarios (Table 2) (totaling nine narrative scenarios S1–S9 in Figure 1) by combining the low, medium, and high pathways of those 15 types of parameters. Details of the nine scenario settings can be found in Figure 1B and Table S5.

Simulation and modeling equations

Car module simulation

The car module is the foundation of the integrated car fleet dynamics model. We use a product stock-driven model[116] in the car fleet dynamics module to simulate the annual total new cars needed ($I_{Car(t,i)}$) from 2019 to 2050 (Equations 1 and 2). The results from Equations 1 and 2 were then decomposed by powertrain technology and segment in a high resolution to obtain the values for new cars needed ($I_{Car(t,p,s,i)}$), scrapped cars ($O_{Car(t,p,s,i)}$), and car-in-use stocks ($S_{Car(t,c,c',p,s,i)}$) (see Equations 3, 4, and 5, respectively). These consequent car stocks and flows results will then feed into the material and emission modules.

$$S_{Car(t,i)} = P_{(t,i)} \times OW_{Car(t,i)} \qquad \text{(Equation 1)}$$

$$I_{Car(t,i)} = S_{Car(t,i)} - S_{Car(t-1,i)} + O_{Car(t,i)} \qquad \text{(Equation 2)}$$

$$I_{Car(t,p,s,i)} = I_{Car(t,i)} \times MS_{Car(t,p,i)} \times MS_{Car(t,s,i)} \qquad \text{(Equation 3)}$$

$$O_{Car(t,p,s,i)} = \sum_{c \le t} \left(I_{Car(c,p,s,i)} \times L_{(t-c,i)} \right) \qquad \text{(Equation 4)}$$

$$S_{Car(t,c,c',p,s,i)} = I_{Car(c,p,s,i)} \times \left(1 - \sum_{c \le t} L_{(t-c,i)} \right) \qquad \text{(Equation 5)}$$

In these equations, $S_{car(t,i)}$ or $S_{car(t-1,i)}$ is the car stock in year t or $t-1$ under scenario i; $P_{(t,i)}$, $OW_{car(t,i)}$, and $O_{Car(t,i)}$ indicate the population, car ownership, and scrapped cars in year t under scenario i; $I_{car(t,i)}$ or $I_{car(c,i)}$ is the sales of cars in year t or c under scenario i; $L(t-c, i)$ is the scrappage rate (derived from survival function or lifetime) of previously registered cars after $t-c$ years under scenario i; $I_{Car(t,p,s,i)}$ or $I_{Car(c,p,s,i)}$ is the new cars introduced into fleet by powertrain technology p, segment s, in year t or c, respectively, under scenario i; $O_{Car(t,p,s,i)}$ is the scrapped cars out from fleet by powertrain technology p, segment s, in year t under scenario i; $S_{Car(t,c,c'p,s,i)}$ is the car stock composition in year t by cohort c, age c', and powertrain technology p, segment s, in year t under scenario i; $MS_{Car(t,p,i)}$ is the market share of powertrain technology p in year t under scenario i; and $MS_{Car(t,s,i)}$ is the market share of segment s in year t under scenario i.

Materials module simulation

The new cars needed with high-resolution powertrain technology and segment will be further translated into relevant material flows (gross demand and secondary provision) based on material intensity, process scrap rate, and lifetime distribution (assumed the same as cars) as shown in Equations 6 and 7, respectively. The primary demand (PD_{Mat}) is further determined by the difference between gross demand (GD_{Mat}) and potential secondary materials supply (calculated based in closed-loop recycling rate) (see Equation 8).

$$GD_{Mat(t,m,i)} = \sum_p \sum_s \left(\frac{I_{Car(t,p,s,i)} \times MI_{(t,p,s,m,i)}}{\left(1 - PR_{(t,m,i)}\right)} \right) \qquad \text{(Equation 6)}$$

$$SS_{Mat(t,m,i)} = \sum_p \sum_s \left(\sum_{c \le t} \left(\left(I_{Car(c,p,s,i)} \times MI_{(c,p,s,m,i)} \right) \times L_{(t-c,i)} \right) \right) \times CLRR_{(t,\ m,\ i)} \qquad \text{(Equation 7)}$$

$$PD_{Mat(t,m,i)} = GD_{Mat(t,m,i)} - SS_{Mat(t,m,i)} \qquad \text{(Equation 8)}$$

$GD_{Mat(t,m,i)}$ is the gross demand for material m in year t under scenario i; $MI_{(t,p,s,m,i)}$ is the material intensity of cars by powertrain technology p, segment s, material m, in year t under scenario i; $PR_{(t,m,i)}$ is the process scrap rate for material m in year t under scenario i; $CLRR_{(t,\ m,\ i)}$ is the closed-loop recycling rate at the end of life for material m in year t under scenario i; $PD_{Mat(t,m,i)}$ is the demand for primary material m from scrapped cars in year t under scenario i; $SS_{Mat(t,m,i)}$ is the secondary supply of material m from scrapped cars in year t under scenario i.

Emissions module simulation

The emissions module includes three parts: drive-cycle, car-cycle, and energy-cycle emissions (see Figure 1 and Equation 9). The drive-cycle emissions (also called direct or operational emissions) refer to emissions from car use and are calculated based on high-resolution time-cohort-type car stocks and corresponding annual kilometrage, use intensity, and annual fuel economy of various car types (Equation 10). The car-cycle emissions include emissions from material (both primary and secondary, derived from the materials module) production, car manufacturing (based on new cars needed derived from the car module), and end-of-life management (based on scrapped cars derived from the car module) (see Equation 11). The energy-cycle emissions include the indirect emissions along the energy supply chain (particularly electricity generation) for all energy consumed in the use and car manufacturing stage (see Equation 12).

$$C_{total(t,i)} = C_{car-cycle(t,i)} + C_{energy-cycle(t,i)} + C_{drive-cycle(t,i)} \qquad \text{(Equation 9)}$$

$$C_{drive-cycle(t,i)} = \sum_e \left(\sum_p \sum_s \sum_c \sum_{c'} \left(S_{car(t,c,c',p,s,i)} \times K_{(t,c',i)} \times Uti_{(c,p,s,r,i)} \times EC_{(c,p,s,e,i)} \times C_{dir(t,e)} \right) \right) \qquad \text{(Equation 10)}$$

$$C_{car-cycle(t,i)} = \sum_m \left(C_{pri(t,m,i)} \times PD_{Mat(t,m,i)} + C_{sec(t,m,i)} \times SS_{Mat(t,m,i)} \right) + \sum_p \sum_s \sum_e \left(I_{car(t,p,s,i)} \times EU_{(t,p,s,\ e,i)} \times C_{dir(t,e,\ i)} \right) + \sum_p \sum_s \left(O_{car(t,p,s,i)} \times C_{ad(t,p,s,\ i)} \right) \qquad \text{(Equation 11)}$$

$$C_{energy-cycle(t,i)} = \sum_e \left(C_{es(t,e,\ i)} \times \sum_{p,s} \left(I_{Car(t,p,s,i)} \times EU_{(t,p,s,\ e,i)} \right) \right) + \sum_e \left(C_{es(t,e,\ i)} \times \sum_p \sum_s \sum_c \sum_{c'} \left(S_{car(t,c,c',p,s,i)} \times K_{(t,c',i)} \times Uti_{(c,p,s,r,i)} \times EC_{(c,p,s,e,i)} \right) \right) \qquad \text{(Equation 12)}$$

In these equations, $K_{(t,c',i)}$ is kilometrage in year t for age c' under scenario i; $Uti_{(c,p,s,i)}$ is the utility factor for cohort car produced in year c by powertrain technology p, segment s, under scenario i; $EC_{(c,p,s,e,i)}$ is the energy consumption by type e per 100 km for cohort car produced in year c by powertrain technology p, segment s, under scenario i; $C_{dir(t,e)}$ is the direct emission intensity for energy type e in year t; $EU_{(t,p,s,e,i)}$ is the energy use (e) for manufacturing a car of powertrain technology p, segment s, in year t under scenario i; $C_{pri(t,m,i)}$ or $C_{sec(t,m,i)}$ is the emission intensity of primary production or secondary production, respectively, of material m in year t under scenario i; $C_{es(t,e,\ i)}$ is the emission intensity of energy supply chain for specific energy types e in year t under scenario i; and $C_{ad(t,p,s,\ i)}$ is the disposal emission of decommissioned cars of powertrain technology p, segment s, in year t under scenario i.

Limitations and uncertainty

Our model results build on many parameters and thus bear unavoidable uncertainties. For example, the lifetime of all car embodied materials is assumed the same as the lifetime of cars (while, in fact, they can be different), and several key parameters, such as the material closed-loop recycling rate at the end of life, were estimated based on literature or industry survey. We have conducted a sensitivity analysis for the effects of different types of parameters or in combination (e.g., integrated car technology that considers fuel economy, lightweight, and powertrain technology share) on cars, materials, and emissions using S4 (Table S6) and S5 (Table S7) as a benchmark, respectively. Using S4 as a benchmark, we show the impact of the change of each type of parameter or in combination on the fleet dynamics (Figures S25–S27), material flows (Figures S58–S63), and emissions (total emissions in Figures S74 and S78, drive-cycle emissions in Figures S77 and S81, car-cycle emissions in Figures S75 and S79, and energy-cycle emissions in Figures S76 and S80). Similarly, using S5 as a benchmark, we show the impact of the change of each type of parameter or in combination on fleet dynamics (Figures S28–S30), material flows (Figures S64–S66), and emissions (total emissions in Figure S82, drive-cycle emissions in Figure S85, car-cycle emissions in Figure S83, and energy-cycle emissions in Figure S84).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.07.005.

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AUTHOR CONTRIBUTIONS

G.L. conceived the original idea. G.L., X. Liu, and Q.G. designed and supervised the research. W.C. and X.S. prepared the data. W.C. and R.Z. developed the Python programming. W.C. and G.L. developed the model, ran the simulation, and drew the figures. L.L., S.Z., M.W., X. Li, Q.S., J.Y., and E.H. enhanced the discussion. W.C. and G.L. drafted the paper. All authors analyzed the results and contributed to writing this paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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