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Reconciling Sectoral Abatement Strategies with Global Climate Targets: The Case of the Chinese Passenger Vehicle Fleet

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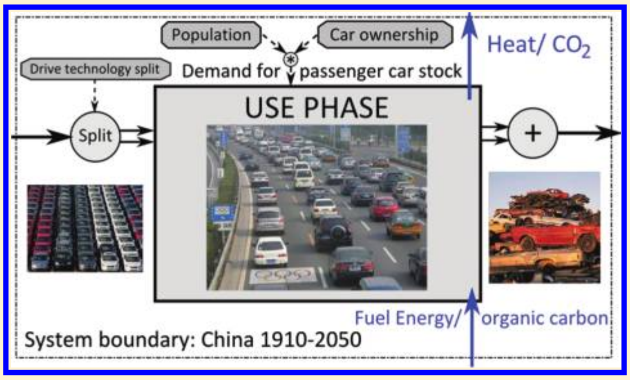
S *Supporting Information*

ABSTRACT: The IPCC Forth Assessment Report postulates that global warming can be limited to 2 °C by deploying technologies that are currently available or expected to be commercialized in the coming decades. However, neither specific technological pathways nor internationally binding reduction targets for different sectors or countries have been established yet. Using the passenger car stock in China as example we compute direct CO_2 emissions until 2050 depending on population, car utilization, and fuel efficiency and compare them to benchmarks derived by assuming even contribution of all sectors and a unitary global per capita emission quota.



Compared to present car utilization in industrialized countries, massive deployment of prototypes of fuel efficient cars could reduce emissions by about 45%, and moderately lower car use could contribute with another 33%. Still, emissions remain about five times higher than the benchmark for the 2 °C global warming target. Therefore an extended analysis, including in particular low-carbon fuels and the impact of urban and transport planning on annual distance traveled and car ownership, should be considered. A cross-sectoral comparison could reveal whether other sectors could bear an overproportional reduction quota instead. The proposed model offers direct interfaces to material industries, fuel production, and scrap vehicle supply.

1. INTRODUCTION

In 2009, the world leaders, including China, struck the Copenhagen Accord to limit global warming to 2 °C by substantially reducing greenhouse gas emissions.[1] The accord is based upon the IPCC Fourth Assessment Report (AR4) that finds "[...] *high agreement* and *much evidence* that all [temperature] stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialized in coming decades, [...]"(Summary for Policy makers of WGIII).[2] However, binding long-term agreements on how and to which extent different countries and sectors should contribute to emission reduction are still a matter of considerable debate.

An overview on proposals for international agreements on climate change mitigation published by scientists is given in Table 13.2 in IPCC AR4-WGIII.[2] Out of the many options proposed this work focuses on sectoral approaches to break down global reduction scenarios onto specific human activities in order to allow for better understanding of the challenge mankind faces.

We want to contribute to the debate on balanced long-term sectoral targets by analyzing a specific case: direct emissions from passenger cars in China until 2050.

Direct emissions from the transport sector accounted for 23% of global carbon emissions from energy and processes in 2005,[3] whereof ca. 50% arose from passenger cars.[4] A recent review by Hertwich[5] confirms the dominance of passenger vehicle fuel in energy use for transportation (≥50%) and the significant contribution of transport to the total carbon footprint of households in industrialized countries (10...50%). Moreover, direct emissions from fuel combustion account for ca. 70% of the life cycle emissions of present passenger cars[6] and ca. 85% of the well-to-wheel emissions of fossil fuels.[3] Hence the lifestyle and the behavior of the end user significantly determine life cycle emissions of passenger cars. Due to their relevance direct emissions from individual transportation are an excellent object to study emission abatement resulting from both energy efficient technologies and different levels of utilization of cars on a sectoral basis. While both IEA[3] and IPCC AR4[2] use the same sectoral boundary as this article, there is a rising interest in the overall impact of transport as an activity, including upstream and downstream emissions, as demonstrated by the work of Kagawa et al.[6] The model we apply returns the inflow and outflow of different cohorts and vehicle types over time and can therefore be used to scale up life cycle inventories of individual cars.

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Table 1. Sectoral Benchmarks for Carbon Emissions from the Passenger Car Fleet in China, 2050, Based on Table 3.10 in IPCC AR4[2,a]

class	CO_2 conc. at stabilization [ppm][2]	global average temperature increase [°C][2]	change in global CO_2 emissions 2000 → 2050 [%][2]	CO_2 emission goal for global passenger car fleet [Gt CO_2/y]	CO_2 emission goal for China's passenger car fleet [Gt CO_2/y]
I	350−400	2.0−2.4	−85 to −50	0.36−1.2	0.06−0.19
II	400−440	2.4−2.8	−60 to −30	1.0−1.7	0.15−0.26
III	440−485	2.8−3.2	−30 to +5	1.7−2.5	0.26−0.39
IV	485−570	3.2−4.0	+10 to +60	2.6−3.8	0.41−0.56
V	570−660	4.0−4.9	+25 to +85	3−4.4	0.47−0.69
VI	660−790	4.9−6.1	+90 to +140	4.6−5.8	0.71−0.89

[a] The benchmarks (right column) were derived by assuming a uniform reduction for all sectors and a unitary global per capita emission quota in 2050: Direct CO_2 emissions from all passenger cars for 2000 (2.4 Gt/yr)[41] are multiplied with the global reduction figures in the middle column and the expected share of Chinese in the world population in 2050 (16%).[22]

Several studies have been conducted to estimate future energy consumption of Chinese passenger cars.[7−11] The latter report[11] estimates future vehicle ownership based on per capita GDP and stresses the importance of a dynamic stock model and technological change.

The necessity of linking future emissions from passenger cars to global warming targets has been recognized by several authors: A recent study by Kagawa et al. relates a dynamic energy model for a constant passenger car stock in Japan to the Kyoto Target.[6] Melaina and Webster[12] developed pathways to reach an ambitious 83% GHG emission reduction target for the U.S. passenger car fleet.

The results of the latter studies however are not directly applicable to China, since neither the future extent of passenger car use is known nor has a specific national and sectoral reduction target been established yet.

We conduct an independent study to build scenarios for future carbon emissions from the growing car stock in China by exploring to which extent energy efficiency and early stage infrastructure planning may compensate for the carbon impact of increasing affluence. Moreover, we propose a simple way of measuring the performance of our abatement scenarios with respect to the various levels of global temperature increase presented in Table 3.10 in AR4-WGIII.[2]

Since passenger car utilization in China is still in its infancy and growing exponentially, we do not extrapolate current domestic statistics or trends until 2050. Instead we conduct our analysis under the premise that eventually, China will develop consumption patterns similar to other industrialized countries:

First, the historic development of individual transportation in developed countries with diverse geographic and demographic characteristics is studied to identify the typical range of car utilization. We establish a baseline by assuming average car utilization in industrialized countries for China and by anticipating moderate improvements of fuel efficiency. Then we combine present observations of relatively low car ownership and annual kilometrage in some developed countries with ambitious reductions in fuel consumption to create a cascade of measures affecting the model parameters in the following order: (1) technological improvement, (2) moderately lower car utilization and (3) a smaller population. The model parameters are changed subsequently to obtain a stack of reduction wedges for sectoral direct CO_2 emissions until 2050.

Instead of finishing the study at this point the contribution of the results to reaching global climate targets should be assessed in addition as awareness of climate change increases. The IPCC AR4 achieves this by comparing the results from isolated sectoral studies to global economic equilibrium model calculations that determine mitigation potentials in all sectors while respecting certain climate targets (cf. Tables 3.13 and 3.14 in AR4-WGIII).[2]

Since transportation is comprised under energy supply for some of the Category I and II studies (which are most relevant for the 2 °C target), only two relevant estimates for 2030 remain. However, these two studies[13,14] rely to a large extent on new technologies such as carbon capture and biofuels to reach the target, whereas we focus on fuel efficiency and lifestyle parameters and do not consider future technologies at the moment (cf. Materials and Methods section). Hence there is no basis for comparing our study with these targets.

Nevertheless we need to benchmark the long-term performance of our sector-specific scenarios with the 2 °C target. We propose a simple alternative for the case where sectoral and country-specific targets have not been established yet or have been established under very different assumptions: We compare the results with the *average reduction quota* this sector would need to contribute if

- By 2050, global GHG emissions were to be reduced according to the *physical targets* presented in Table 3.10 in IPCC AR4,[2]
- All sectors would contribute equally and
- All people would be assigned an equal annual emission budget.

This benchmarking process immediately relates the scenario results to all long-term stabilization categories in IPCC AR4[2] and explicitly uses global climate targets as physical scale.

It identifies the challenge climate change mitigation poses onto different sectors and—if many sectors are analyzed in a similar way—it may facilitate the agreement on sector-specific targets. The corresponding benchmarks for passenger cars in China are developed in Table 1.

2. MATERIALS AND METHODS

The stock driven dynamic MFA model introduced by Müller[15] is applied to cars and extended to not only track different vintages but also different drive technologies as well as their respective direct energy consumption and CO_2 emissions (Figure 1). The passenger car stock is the only process in the system; it is driven by Population (P) and car ownership (C). A vehicle lifetime distribution with mean L establishes a causal relationship between inflow and outflow of individual cohorts. The annual kilometrage (K) and fuel consumption per km (F) for all model years, cohorts, and drive technologies as well as the CO_2 intensity of gasoline determine direct energy demand and emissions.

Two drive technologies are considered: conventional gasoline/diesel and low consumption cars. The latter are vehicles that for the sake of fuel saving are built smaller, lighter, or apply advanced technologies such as regenerative breaking while providing less utility or being more expensive than a conventional car. Their share in car sales is denoted by T. Hybrid electric cars are classified based on their net fuel consumption as either conventional or low consumption cars.

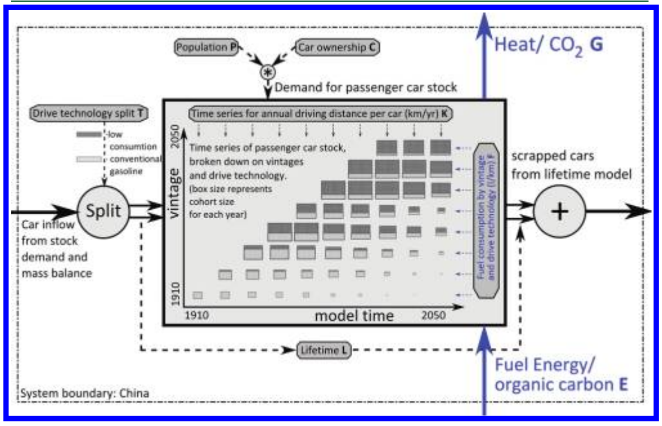

Figure 1. Dynamic model for stock and flows of material (Chinese passenger cars), direct energy (fossil fuel), and direct carbon emissions, 1910–2050.

Conventional diesel cars are not included explicitly since they face severe government constraints due to China's limited supply of diesel, and sales have been negligible in the past.[16] Although their slightly lower relative carbon emissions[17] can contribute to increase the fleet average fuel efficiency, the overall impact in the case of China is considered negligible.

Electricity and biofuels can substitute oil- or coal-based fuels in transportation, and in China their application is promoted mainly to curb oil demand.[18] However, their net contribution to climate change is still under debate: Coal based power plants must be equipped with cost-effective carbon capture and storage (CCS);[18] and for biofuels, emissions from land-use change[19] and the amount of land that can be dedicated to fuel farming need to be assessed. There are plans for planting 130 000 km^2 of *Jatropha* forest in Southern China with an annual production of 6 million tons of biodiesel[20] which still would be a tiny amount compared to expected future demand (cf. Results Section). Moreover, a case study for 10 000 km^2 of *Jatropha* plantations in the same region revealed negligible impact on total GHG emissions.[21] Hence, unless CCS or photovoltaics are implemented on a large scale and a major shift to electric vehicles occurs, direct emissions from combustion of oil-based gasoline represent a reasonable approximation of the carbon footprint of the Chinese passenger vehicle fleet.

Below we describe the specific parameter choices and assumptions, more details are provided in Supporting Information Section S4.

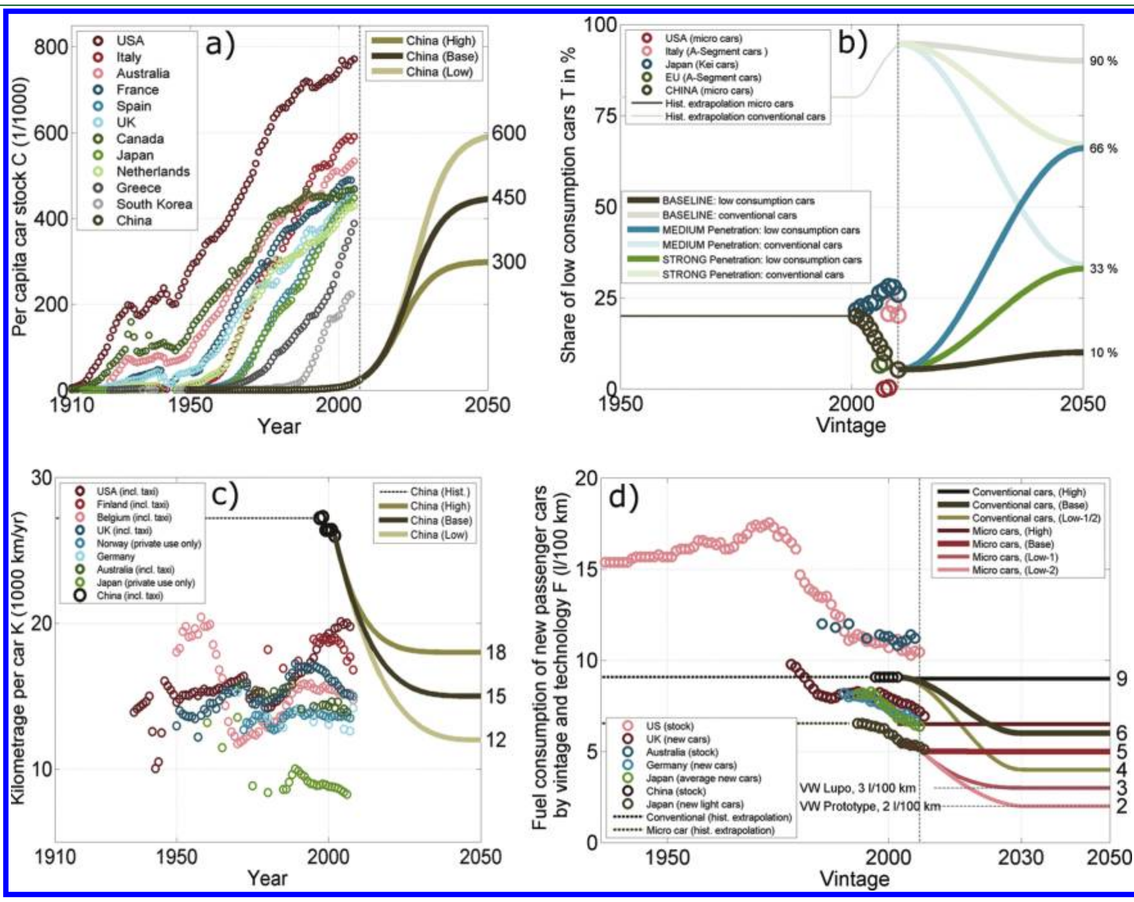

Figure 2. Historic data and future scenarios for cars per capita C (a), share of micro cars T (b), annual kilometrage K (c), and fuel consumption per 100 km F (d).

Population (P) (Supporting Information Figure S1). The UN population division estimates China's population to be between 1.25 and 1.6 billion in 2050, with a mean of 1.4 billion.[22]

Car Ownership (C) (Figure 2a). Although car ownership varies greatly among different countries the historic development reveals some patterns: after a period of slow growth, a kick-off occurs and car ownership grows continuously until it reaches several hundred per 1000 people whereupon its growth is slowing down. The kick-off level becomes smaller in the course of time and countries that industrialized later than others tend to have a steeper penetration curve.[23]

A continuously growing car stock accompanied by transportation infrastructure extension is regarded as a central pillar of China's future economic development.[24] We therefore assume that car ownership in China will follow a similar pathway as observed in many developed countries with very different population sizes and densities (e.g., Japan, U.S., Canada) and apply a logistic growth curve with saturation levels covering the range of car ownership for those countries where it has started to level out: 300 (Low), 450 (Base), and 600 (High) cars per 1000.

Drive Technology Share (T) (Figure 2b). In 2010, the share of micro and other low consumption cars in new registrations (T) had fallen to around 5% (baseline). However, engine size-based vehicle sales excise taxes are already in place to encourage the purchase of smaller vehicles. The share of micro cars is expected to increase gradually because of their affordability and relatively low fuel consumption.[25] The baseline assumes a slow reversal of the current trend by slightly increasing micro car share to 10% by 2050, based on the present share of "city cars" in developed countries.

Given the general accepted importance of further increases in energy efficiency, we propose two alternative scenarios to model the transition to a fleet of micro, lightweight, or low consumption hybrid electric vehicles. We assume the share of low consumption cars to boost to 33% (medium) and 66% (strong) by 2050. All three curves apply an S-shaped section of the cosine function which has zero slope both in 2010 and 2050. Unlike the other parameters, the proposed alternative shares of low consumption cars are not based on historic evidence but reflect a trend reversal.

Kilometrage (K) (Figure 2c). The annual distance traveled (kilometrage) in industrialized countries lies between 12 000 and 20 000 km/year and car (Japan only 8000 km/yr, author estimate). In the U.S. kilometrage keeps on increasing due to longer commuting distance and expanding suburbs.[26] In contrast it has been fairly constant over time both in Norway and Belgium and it even started declining in Germany, the UK, Australia, and Japan. The few historic data points for kilometrage in China are much higher (27 000 km/year). This can be explained by the high share of taxis in the passenger car fleet (16% in 2002) which have an annual kilometrage of 90 000 km/yr.[11]

Although the countries in Figure 2c are very different in size (e.g., Belgium and Australia) and population density (e.g., Norway and Germany) their annual kilometrages follow a similar pattern. We therefore assume that kilometrage in China eventually will be in the range of other developed countries. Data for Japan had to be estimated (Supporting Information Section S4) and do not include taxis. We therefore do not consider this value in our scenarios.

Given the historic range of kilometrage we assume an asymptotic development toward 18 000 km/year (high), 15 000 km/year (base), and 12 000 km/year (low) for China (cf. Supporting Information Section S4).

Fuel Consumption per 100 km (F) (Figure 2d). The time series for the U.S. and Australia represent the fleet average while for Japan, Germany, and the UK only the respective latest cohort is considered. Fuel efficiency has improved significantly over the last decades. The Base scenario incorporates that already today increasing fuel efficiency is a major concern of car makers. Examples for low consumption cars are the VW Lupo 3 L (3 L/100 km) and the VW XL1, a prototype hybrid electric car that achieves about 2 L/100 km on long distances.[27] These cars serve as reference for the Low scenarios where we assume fuel consumption of 2030 micro cars to be 3 L/100 km (scenario Low-1, not discussed in the paper) and 2 L/100 km (scenario Low-2), respectively. For conventional cars we assume fuel consumption to settle down at a higher level (4 L/100 km for both Low-1 and Low-2). For the baseline we assume a gradual, but less ambitious decrease to 6 L/100 km for gasoline conventional and 5 L/100 km for micro cars bought in 2030. For the high scenario we assume the cohort average to remain at the present high values as increasing car size and level of equipment such as air conditioning may hinder a further reduction of fuel consumption.

We further assume that by 2030, the reduction potential that today's prototypes and similar vehicles offer will be exhausted. The resulting fleet average is shown in Figure 4.

Lifetime (L) (Supporting Information Figure S2). A normally distributed lifetime with a mean of 15 years (Base) as recently observed in Beijing[28] and gradual change to 12 years (Short) and 18 years (Long) is applied. The standard deviation is 40% of the mean.

Compared to all other parameters, lifetime has much smaller impact on direct energy consumption and emissions (Figure 3). We therefore refer to Supporting Information Section S4 for a detailed discussion of this parameter.

The baseline is obtained by setting all parameters to their respective bases. Maximal and minimal car throughput is determined by combining high population, high car ownership, and short lifetime to obtain the largest car stocks and flows, and vice versa.

Parameter Wedges and Bottom Line. Starting from the baseline, we change one parameter after the other to determine the wedge each parameter may contribute to emission abatement. The parameters are ranked according to their respective impact on peoples' lifestyle: First we change fuel consumption to its minimum since this is a purely technological parameter. Then, we equip first $^1/_3$ and then $^2/_3$ of the people with low consumption cars which may be less attractive or more expensive. In order to achieve further reduction people need to change their behavior and lifestyle according to Figure 2: First, we propose a lower car use by lowering kilometrage, followed by an even more severe change in form of lower car ownership. A lower future population is the last resort in our ranking.

Finally, we arrive at the bottom line which is has the lowest energy throughput of all possible combinations of parameter variations (cf. Supporting Information Table S4).

3. RESULTS

Car Stock and Flows. For the baseline, the Chinese passenger car stock will reach about 630 million by 2050, compared to 38 million in 2008 (Figure 3a). Car ownership has a much higher impact on the vehicle stock than population (420...630...830 million vs 570...630...700 million). Even for low car ownership

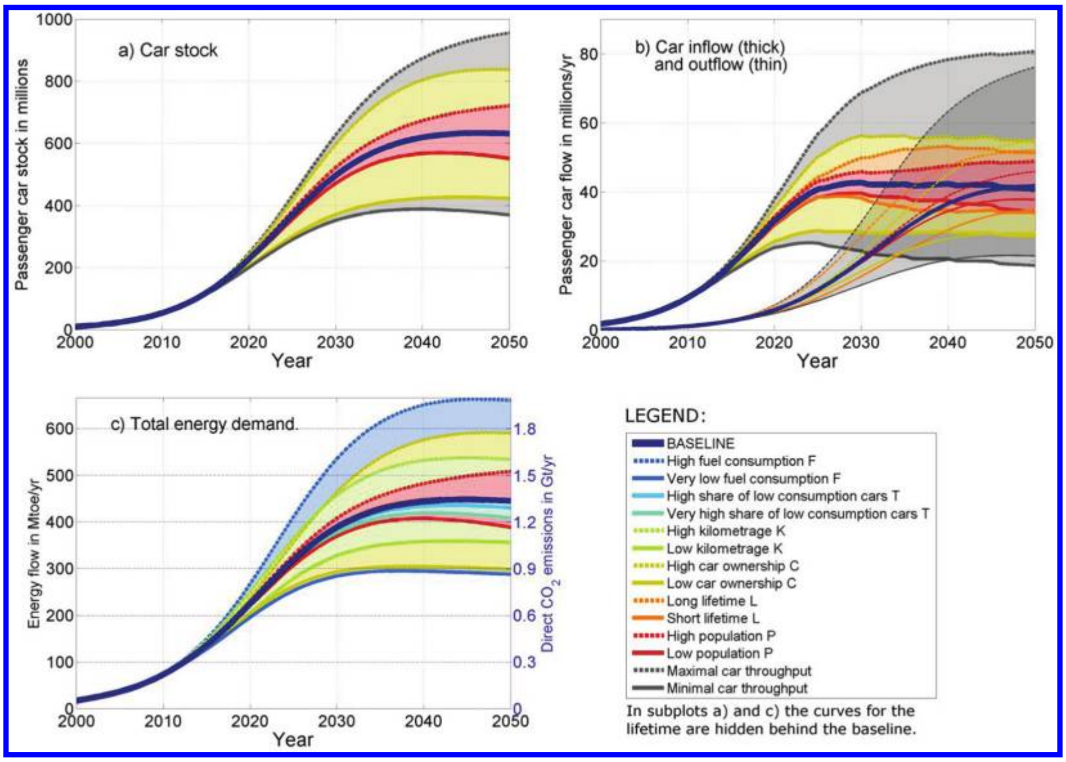

Figure 3. Absolute sensitivities with respect to changes in individual model parameters according to the scenario definition: (a) car stock; (b) car flows; (c) total energy demand and emissions.

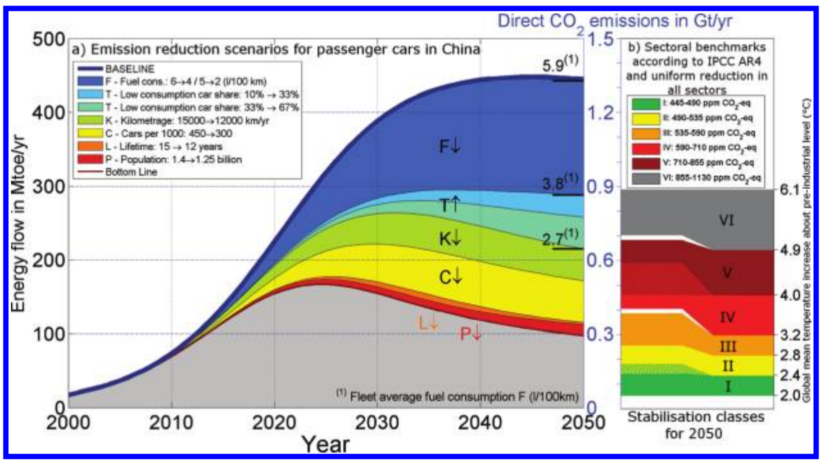

Figure 4. Plot (a) Wedge plot of direct energy consumption (left axis) and CO_2 emissions (right axis) for passenger cars in China. Starting from the baseline all six model parameters are successively changed according to Supporting Information Table S4 to yield lower energy throughput. Plot (b) Sectoral benchmarks for carbon emissions (sharing left axis with plot (a) derived from the six classes of temperature increase (right axis) in IPCC AR4 assuming even contribution of all sectors and a uniform global per capita emission quota in 2050.

the Chinese vehicle stock will exceed the 2008 U.S. passenger car stock of 140 million[29] at the latest around 2018. To build up and sustain the stock, both new registration and the flow of scrapped cars will vastly increase during the next decades (Figure 3b). By 2050, the baseline forecasts new registration and scrap flow to ca. 40 million/year. For high car ownership, domestic passenger car sales will equal the 2009 world passenger car production of ca. 48 million cars[30] by about 2023.

The impact of car ownership (yellow) on the inflow is about twice as high as the impact of population (red) and lifetime (orange). In contrast, car outflow is initially mainly dependent on lifetime while car ownership becomes more relevant only after around 2040. The combined impact of the three parameters is very large, allowing for car inflows between 20 and 80 million/year in 2050.

Absolute Sensitivity of Energy Consumption and CO_2 Emissions. For the baseline, total energy demand raises to about 450 Mtoe/year by 2050 which corresponds to direct CO_2 emissions of about 1.3 Gt/year (Figure 3c). The plot allows to rank the different single parameter variations according to their respective impact on energy demand compared to the baseline:

Choosing lower fuel consumption will change energy demand by ca. +45/−30%, followed by ±35% for lower car ownership and ±20% for lower kilometrage. Even a massive shift in peoples' preferences toward micro cars would lower energy demand by only ca. 8%. A lower population scenario would lead to ca. 13% lower emissions. The effect of lifetime is minimal and hidden behind the baseline.

Wedges of Parameter Variations. For a typical increase in car utilization (baseline) emissions will rise significantly (Figure 4a). An absolute decrease may occur only after 2025 if car ownership, kilometrage, and the share of low consumption cars change in addition to fuel efficiency.

The largest contributor to emission reduction is a substantially lower fuel consumption which by 2050 would decrease the fleet average from 5.9 to 3.8 L/100km. With a wide use of low consumption cars 2.7 L/100km are possible. Only by exhausting the potential for improving fuel efficiency and shifting to smaller or lighter cars, emissions could be reduced by a factor of ca. 2 compared to the baseline.

Taking this "technological bottom line" (the bottom of the cyan-colored wedge) as reference, lifestyle changes attributable to kilometrage and car ownership can yield a further reduction of about 45% by 2050 in which the impact of car ownership is highest. The wedges for lifetime and population are much smaller than the other ones. Still their consequences should not be underestimated: Realizing the lifetime wedge would increase car production and related impacts by ca. 25% and the red wedge corresponds to a population difference of 170 million people.

When comparing emissions in 2050 to the different benchmarks we find that focusing on fuel efficiency alone will in the best case correspond to class VI (Figure 4b). Vastly increasing the share of small cars and lowering kilometrage in addition would be sufficient to reach classes V and IV, whereas only by an additional reduction of car ownership, the class III benchmark can be met. Classes II and I are unachievable: The bottom line is a factor of 1.5...5 apart from the class I benchmarks. Even if all wedges are included the resulting bottom line performs much worse than the average requirement for limiting global warming below 2 °C.

When assessing the long-term predictions from the previous studies[7−11] within the framework of Figure 4, we find that all scenarios proposed there fall into class V or upward. This illustrates that many long-term forecasts will have to be rethought in light of climate change. A detailed comparison is provided in Supporting Information Section S6.

4. DISCUSSION

The scenarios reflect China's efforts to catch up with western lifestyle while limiting dependency on oil imports and curbing GHG emissions by shifting toward very fuel efficient technologies and moderately adjusting lifestyles. This way, direct emissions can be reduced by almost 80% compared to the present average level in industrialized countries. Although simply adding up some of the individual sensitivities shown in Figure 3c suggests a much higher overall reduction for a combined scenario, this is not the case. The reason is that applying a certain measure to the stock, for example, fewer cars, lowers the potential impact of the subsequent measures in the cascade, for example, lower fuel consumption.

Especially for scenarios with many wedges, large relative variations of single parameters, or ambitious reduction targets the bottom line might be substantially higher than one would expect from several disconnected ceteris paribus calculations (cf. also Pacala and Socolow[31]).

There is a clear mismatch between even the most ambitious scenarios and the emission benchmark for a 2 °C global temperature increase. More research with an extended system boundary is therefore required to find reasonable targets for emissions from passenger cars and other sectors. In particular we see a need to

(1) Reconsider the reduction potentials of annual kilometrage and car ownership as well as fuel efficiency and connect them to research on urban planning and shift of transport modes.
(2) Assess the potential impact of low-carbon fuels in various countries by introducing CCS, electric vehicles, or a partial shift to biofuels.
(3) Develop a sector-specific target which may allow for higher-than-average transport emissions while tougher goals would have to be implemented in e.g. buildings or material producing industries.

(1) There is no commonly accepted bottom line of fuel consumption for gasoline driven cars because there is no agreement on the minimum functionality of such vehicles and hence, average fuel consumption might go below 2.7 L/100 km. However, for vehicles that are both suitable for city driving and taking a family of four on a holiday, a fleet average of less than 3 L/100km is very ambitious. Future car ownership could be reduced further but the role of cars as status symbol in China[32] may limit the abatement potential of this option. A bigger potential may lie in further reducing kilometrage as this measure does not conflict with the mentioned role of cars.

All these suggestions remain speculative however and may lower the quality of life unless we expand the system boundary to identify sustainable transport solutions in a larger context.

The share of urban population in China increases rapidly and the difference in income between urban and rural population is substantial.[33] Cars mainly used within cities are likely to constitute a major share of the future stock and urban planners should take into account the effect of their city design on people's driving patterns and their decision on whether to have a car or not. Adjusting the density of settlements, efficient public transport systems, or mixed use development are planning options that can lead to lower kilometrage and car ownership.[34,35] City structures and road patterns that are planned today will set the course for the driving behavior of the residents for the coming decades. Now, China has the unique opportunity to build cities that allow for low impact transportation in the first place. However, there are still gaps in understanding the connection between urban structure and the carbon impact from transportation.[36]

(2) Coal is expected to play a major role in China's energy supply in the decades to come and its energy may as well be applied in transportation as a study by Ou et al.[18] suggests: Compared to oil-based fuels, life cycle emissions of a passenger car kilometer may be lowered by up to 60% for an electric vehicle, if highly efficient carbon capture and storage is applied at the power plant.

In a different study[37] Ou et al. find big variations between different present biofuel pathways. While all investigated biofuels reduce dependency on oil, only three of them reduce GHG emissions with *Jatropha*-based diesel having a potential of saving up to 50% per kilometer driven; a result that is, however, not confirmed by the larger-scale assessment cited above.[21]

More comprehensive, China-specific studies that transform small-scale results into a determination of the large scale mitigation potential are required; and one must bear in mind that other sectors may want to draw on these alternative energy sources as well to reach their carbon target.

(3) Less substantial emission reductions could be allocated to passenger cars if other sectors could achieve reductions beyond the average. A recent white paper from the European Commission indeed assigns a looser reduction target to the transport sector[38] which is supposed to be compensated by virtually carbon-free electricity and tremendous energy savings in buildings and industry.

The latter two sectors are the two major contributors to energy-related carbon emissions (33% and 36%, respectively).[39]

There is much evidence for an emission reduction potential of at least 29% within the building sector until 2030,[2] and some *passive houses* can save up to 90% compared to the present consumption.[40] This sector may have a large saving potential which might potentially compensate for higher emissions from other sectors.

Industries, especially those for basic materials, are unlikely candidates for disproportionately high emission cuts as they are dependent on the arrival of cost-effective breakthrough technologies including CCS to reach their target if primary production increases as expected. Large-scale recycling alone has been found to be insufficient to reach a 50% emission cut.[39] Anyway the responsibility of material processing industries will increase since their share in life cycle emissions of houses and cars will rise as the latter become more energy efficient during use.

Throughout the work we assumed that the six parameters that drive fuel consumption are independent. However it is clear that rebound effects may occur, for example, when a drastically reduced fuel consumption leads to increased annual kilometrage or higher vehicle sales (direct rebound), or increased spending in other sectors (indirect rebound). Both effects may further exacerbate emission reduction both within the sector and in total. It is therefore of utmost importance that serious climate change mitigation takes a cross-sectoral system perspective which simultaneously assesses options within the individual sectors that go beyond a mere focus on energy efficiency or carbon intensity, for example by taking into account both technological *and* lifestyle parameters.

The model allows for easy inclusion of various type- and vintage-specific material stocks and flows which would provide a direct interface to various material cycles and their energy supplies. This extension could help to model material quality issues in future recycling, discover potential resource scarcities, for example, in connection with electric vehicles, and provide a more comprehensive ecological footprint in the mid- and long-term horizon.

For the years after 2030, the scenarios represent a mature car stock of an industrialized society. They hence apply to all countries that need to curb energy related emissions while keeping mobility on a high level. On the other hand the present lack of infrastructure and other capital in developing economies actually may represent a substantial advantage as it allows for early orientation toward a development with lower material and energy throughput, which may help to create a society which is less dependent on fossil energy and hence has correspondingly lower carbon emissions.

With industrialization and urbanization just started, early stage planning and decisions may help China to become less dependent on individual transport than, for example, the U.S. and may facilitate reaching future emission reduction targets.

■ ASSOCIATED CONTENT

S Supporting Information. We provide system definition and complete model approach as well as all data sources and additional results. This material is available free of charge via the Internet at http://pubs.acs.org.

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