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

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Can the Chinese Passenger Car Fleet Contribute Its Share to Limit Global Warming to 2°C?

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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 reduction targets for different sectors have been established. Using direct CO_2 emissions from the growing passenger car stock in China as example, we investigate whether it is sufficient to focus on reductions within the different sectors of energy use while assuming even contribution of all sectors and a unitary global per capita emission quota. We performed a dynamic Material Flow Analysis on the passenger car stock to compute future direct CO_2 emissions depending on population, car utilization, and fuel efficiency.

Massive deployment of present prototypes of fuel efficient cars can reduce emissions by about 45% compared to average car use in industrialized countries; moderately lower use could contribute with another 33 %. Still, emissions remain about two times higher than the 2˚C target and hence, alternative fuels, more significant lifestyle changes, or reduction potentials beyond the sector boundary have to be explored. The proposed model facilitates the necessary extension as it offers direct interfaces to material industries, fuel production, and supply of scrap vehicles.

KEYWORDS: GHG emission abatement; IPCC; Global warming target; Passenger Cars; China;

1. Introduction

In order to limit average global temperature rise, the IPCC Fourth Assessment Report[1] suggests a set of reduction and curbing scenarios for global CO_2 emissions. At the U.N. Climate Change Conference in Copenhagen in 2009, the world leaders, including China, struck an accord with the goal to limit global temperature increase to 2˚C, corresponding to an emission reduction by 50 to 85% from 2000 levels. According to IPCC AR4, there is "*high agreement* and *much evidence* that all 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, assuming appropriate and effective incentives are in place for their development, acquisition, deployment and diffusion and addressing potential barriers".[2]

However, the IPCC scenarios are not specific in identifying suitable combinations of technologies and their diffusion rates in order to sufficiently understand the various challenges and opportunities associated with different emission targets.

One option to become more specific is to consider different sectors of energy use and to identify and assess emission reduction potentials within the boundary of the respective sectors.

As an example of the sectoral approach we focus on direct emissions from individual transportation in China and examine to which extent ambitious technological improvement and moderate lifestyle changes can contribute to emission abatement.

Direct emissions from the global transport sector were about 6 Gt of CO_2 or 23% of global carbon emissions from energy and processes in 2005,[3] whereof 50% arose from passenger car use. In China energy use in transportation grew from 5 million tons of oil equivalent (Mtoe) per year in 1980 to 130 Mtoe/yr in 2008;[4] its limited natural gas and petroleum resources make China the second-largest net oil importer after the U.S.[5]

Continuous improvement of the living standard in China leads to increasing demand for transport services, particularly for private vehicles. Despite its rapidly growing economy, China's level of motorization – in 2008 at approximately 29 passenger vehicles per 1,000 people[6] – is still more than a factor of ten lower than that of most developed countries. A convergence towards western standards during the coming decades will have to be reconciled with the risks of oil import dependency and climate change.

Several studies have been conducted to estimate future energy consumption of Chinese passenger cars.[7-11] In the latter report[11] the importance of a dynamic vintage approach and technological change is emphasized and future vehicle ownership is estimated based on per capita GDP.

The necessity of linking future passenger car use to global warming targets has been recognized by several authors: A recent study by Kagawa and colleagues relates a dynamic energy model for a constant passenger car stock in Japan to the Kyoto Target.[12] Melaina and Webster[13] developed pathways to reach an ambitious 83 % GHG emission reduction discussed by the US government.

China as a developing economy however is likely to prioritize extended passenger car utilization as a form of economic development over emission curbing, a strategy that is in line with point 2 of the Copenhagen Accord.[14] Above all it is therefore necessary to find robust forecasts of future car utilization and secondly, to identify potentials for changing use patterns and to estimate the impact of currently available fuel efficient technologies in a developing market.

Moreover, Melaina and Webster refer to US emissions as reference. The IPCC reduction scenarios however acknowledge the global nature of climate change and hence its scenarios refer to worldwide emissions of 2000 which together with the reduction targets presented makes those scenarios much harder to achieve. We therefore see the need to conduct a study adapted to a developing car stock that estimates the impact of the at present best available technology based on internal combustion engines and that relates direct emissions from this sector to global GHG emission reduction targets.

Our study (i) quantifies the impact of population, cars per capita, annual kilometrage, and fuel efficiency on passenger car utilization and direct energy demand, (ii) assesses the sectoral CO_2 emissions reduction potential of the passenger car fleet, and (iii) determines whether the passenger car fleet could bear a proportional share of GHG emission reductions for different global warming targets assuming deployment of vehicle technologies that are either available or that are expected to become available over the next decades.

For (i) and (ii) we analyze patterns of historic development of individual transportation in developed countries to estimate a baseline and alternative scenarios for lower car utilization for China. Trends for medium and low car ownership and annual kilometrage are combined with ambitious reductions in fuel consumption by scaling up presently available prototypes of cars with internal combustion engines.

For (iii) we derive at set of sectoral emission targets based on IPCC AR4 (Table 1).

To assess the potential for abatement of direct emissions we propose 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 parameters are changed subsequently to obtain a stack of reduction wedges which is contrasted with the sector targets derived from IPCC AR4.

Our model allows to link peoples' lifestyle to the utilization of passenger cars and to track different vintages through their respective life cycle. The impact of both lifestyle changes and improved technology (fuel efficiency) on emission reduction can be assessed several decades in advance. Comparing the bottom line of direct emissions to the sector targets derived reveals the limit of sectoral approach. Our model can be easily extended by connecting to upstream industries and material production, fuel production, and downstream supply of scrap.

2. Methodology

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 energy consumption and CO_2 emission (Fig. 1). The stock model is driven by Population P and lifestyle in terms of car ownership C. A normally distributed vehicle lifetime 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 are introduced in order to determine direct energy demand and emissions.

Two drive technologies are considered: conventional gasoline and low consumption cars. The latter include micro cars and their share in the annual inflow is denoted as T. Hybrid electric cars are classified based on their net fuel consumption as either conventional or low consumption cars.

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-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. A case study for one million ha of Jatropha in South-West China revealed negligible impact on total GHG emissions.[20] Unless CCS is implemented on a large scale over the coming years, direct emissions from gasoline-powered cars serve as reasonable proxy for emissions induced by a switch to alternative fuel vehicles.

Scenarios for the model parameters C and K are created by identifying patterns of historic development in industrialized countries that serve as reference for the future trajectory in China. National passenger car statistics, population forecasts, and existing prototypes of low consumption cars are applied to calibrate or determine L, P and F. Informed estimates were made for the share of low consumption cars T.

Population (P): According to the UN medium scenario, China's population mean will reach 1.4 billion in 2050, ranging from 1.25 to 1.6 billion.[21]

Cars per person (C): Although car ownership varies greatly among different countries which may be attributed to differences in income levels and development stages, the historic development reveals some patterns (Fig 2a): after a period of slow growth, a kick-off occurs and the car stock grows continuously until it reaches several hundred per thousand people, whereupon its growth is slowing down. The kick-off level becomes smaller in the course of time. There is a tendency that countries that industrialized later than others have a steeper penetration curve.[22]

The Chinese passenger car stock increased from 6 million in 1998 to approximately 38 million in 2008.[6]

A continuously growing car stock accompanied by transportation infrastructure extension is regarded as a central pillar of China's future economic development.[23] The High scenario for C incorporates extensive car use due to high affluence, expansion of the road network, and increased need for personal transportation in rural areas.

The medium variant reflects the average level of cars per capita in industrialized countries.

For the Low scenario we assume that Chinese authorities will soon constrain private vehicle use to curb energy consumption and to reduce traffic congestion.

Share of low consumption cars (T): We differentiate two different drive technologies according to their respective fuel consumption (Fig 2b). Nowadays, low consumption cars comprise micro cars which are defined as passenger vehicles shorter than 3.5 m and with an engine capacity ≤ 1 liter.[24] In the future, hybrid electric vehicles may account for an important share of this class.

The Baseline assumes a share of 10% of total car sales in 2050, based on the present share of ‘city cars’ in developed countries. Vehicle sales excise taxes based on engine size 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.[10]

We therefore propose two very distinct scenarios to model the transition to a fleet of micro, lightweight, or efficient hybrid electric vehicles. We assume T to boost to 33% and 66% of total sales in 2050 for Medium and Strong penetration, respectively.

Distance Traveled (K): Annual kilometrage in industrialized countries lies between 12,000 and 20,000 km/year and car (Japan only 8000km/yr, author estimate), while the kilometrage in China is much higher (27,000 km/year) (Fig. 2c).

In the U.S. K keeps on increasing due to longer commuting distance and expanding suburbs.[25] In contrast K has been fairly constant over time both in Norway and Belgium and it even started declining in Germany, the UK, Australia, and Japan. The high level of historic K in China (26,000-27,000 km between 1997 and 2002) can be explained by the high share of taxis in the passenger car fleet (16 % in 2002).[10] We assume that eventually, due to an increasing number of private cars, K will lie within the range of other developed countries. For the High scenario K will decrease and eventually reach 18,000 km/year by 2050, representing the current level in the US.

For the Base scenario K will decrease to 13,000 km/year by 2050, which is about the current level in Norway, Belgium, Germany and Australia.

The Low scenario reflects that advanced traffic planning could allow for shorter trips, encourage biking, walking, and telecommuting instead of physical traveling. Here K will decrease to 8,000 km/year in 2050, representing the current estimate for Japan.

Fuel consumption (F): 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 (Fig 2d). 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. We assume a gradual decrease to 7 l/100km for gasoline conventional and 5 l/100km for micro cars bought in 2030, respectively. The High scenario assumes the cohort average will remain at the present high values as increasing car size and level of equipment may hinder a further reduction of F. On the other hand car manufacturers are capable of producing passenger cars of considerably lower fuel consumption already today. Examples are the VW Lupo 3L (3 l/100km) and the VW XL1, a hybrid electric car that achieves about 2 l/100km on long distances.[26] These cars serve as reference for the Low scenarios where we assume F of 2030 micro cars to be 3 l/100km (scenario Low-1) and 2 l/100km (scenario Low-2), respectively. For conventional gasoline cars we assume F to settle down at 4 l/100 km (both Low-1 and Low2).

We assume that by 2030, the reduction potential of today's prototypes and similar vehicles will be exhausted.

Lifetime (L): A long functional lifetime can reduce demand for new vehicles but it may also delay the penetration of new technologies. Based on national scrapping standards for vehicles which lay down a maximum age or mileage that can however be extended if the vehicle fulfills a set of requirements,[10] we assume a normally distributed lifetime with mean τ and standard deviation σ as in a study of Müller et al.[27] τ is chosen to be 18, 15, and 13 years for the Long, Medium, and Short scenario, respectively. σ is set to 30% of the mean τ.

The **Baseline scenario** is obtained by setting all parameters to their respective mid values, except T which is set to Low.

Maximal and minimal car throughput are determined by combining the single parameter variations of P, C, and L: high P, high C, and short L result in the largest car stocks and flows, and vice versa for low P, low C, and long L.

Bottom Line scenario and parameter wedges: The Bottom Line is defined as the combination of all single parameter variations that shows the lowest energy throughput. It reflects industrialized countries with lower-than average car utilization and the lowest fuel consumption that would be practically possible today. 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 F to Low-2 since this is a technological parameter that does not substantially alter the service the car provides. Then, T is increased in two steps, thus equipping first 1/3 and then 2/3 of the people with low consumption cars. In order to achieve further reduction people must change their behavior and lifestyle. First we propose to lower the utility of cars by lowering K e.g. through shifts of transport mode. Having more people managing without cars (low C) would be an even more severe change. Population control (low P) is the last resort in our ranking.

3. Results

Car Stock and Flows: For the Baseline, the Chinese passenger car stock will reach about 640 million by 2050, compared to 38 million in 2008 (Fig. 3a). Car ownership C has a much higher impact on the vehicle stock than population P (420…640…850 million vs. 550…640…700 million). Even for low C the Chinese vehicle stock will exceed the 2008 US passenger car stock of 140 million[28] at the latest around 2018. Both car consumption and the flow of scrapped cars will vastly increase during the next decades (Fig. 3b). By 2050, the Baseline forecasts a car inflow of 43 million/year and car outflow of 40 million/year. For high C, domestic passenger car sales will be equal to the 2007 world passenger car production of 53 million cars[29] by about 2034.

The impact of a change in C (yellow) on the inflow is about two times bigger than the effect of a change in P (red) and L (orange). In contrast, car outflow is initially mainly dependent on L, while C becomes more relevant only after 2035. The combined impact of reductions in P, C, and L is large, allowing for car inflows between 20 and 75 million/year in 2050.

Absolute sensitivity of energy consumption and CO2 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 (Fig. 3c). The plot allows to rank the different single parameter variations according to their respective impact on energy demand compared to the Baseline: Choosing the alternatives for K will change energy demand by about ±40 %, followed by +30/-45 % for F and ±35% for C, respectively. Even a massive shift in peoples' preferences towards micro cars (T) would lower energy demand by only 15 %. The same figure holds for a changing population P. The effect of lifetime L is minimal and hidden behind the Baseline plot.

Wedges of parameter variations: Emissions will continue to rise due to increasing affluence. An absolute decrease only occurs after 2020 if K, C, or T are changed in addition to F (Fig. 4).

The largest contributor to emission reduction is a substantially lower fuel consumption which by 2050 would decrease the fleet average from 6.8 to 3.8 l/100km. With a wide use of low consumption cars 2.8 l/100km are possible. Thus, only by exhausting the technological potential and shifting to smaller cars, emissions could be reduced by a factor of ca 2.5 compared to the Baseline.

Taking this 'technological bottom line' (the bottom of the T-wedge) as a reference, lifestyle changes attributable to kilometrage and car ownership can yield a further reduction of about 45 % in 2050, where the impact of K is bigger the one of C in the years before ca 2040, and vice versa afterwards. The P wedge is much smaller than the other ones. Still the impact of this wedge should not be underestimated: it corresponds to a population that in 2050 will be 170 million smaller than the medium value.

When comparing emissions in 2050 with the different targets we derived from IPCC AR4 we find that focussing on fuel efficiency only will in the best case correspond to class VI with a global warming of more than 5 °C (Fig 4). Vastly increasing the share of small cars and lowering K in addition would be sufficient to reach classes V and IV whereas only by a reduction of C, class III and a warming of less than 3 °C is within reach. With the present system boundary and the suggested parameter choices the classes II and I are out of reach: The Bottom Line is a factor of 1.5…3 apart from reaching the class I realm (2...2.4 °C); focussing on fuel efficiency alone leads to emissions that still are about 6 times higher than the quota for class I.

4. Discussion and Conclusion

For the years after 2030, the scenarios represent a mature car stock of an industrialized society. They do not apply to China alone, as other countries may face similar challenges when it comes to curbing energy related emissions while keeping mobility on a high level.

The scenarios reflect China’s efforts to catch up with western lifestyle while limiting dependency on oil imports and curbing GHG emissions by shifting towards best available technologies and moderately adjusting lifestyles. This way, direct emissions can be reduced by about 75% compared to present car use in industrialized countries and moderate improvement of fuel efficiency. However, the sectoral approach we present proved insufficient to achieve the 2 °C goal recorded in the Copenhagen Accord (Fig. 4), although the six single parameter changes (Fig. 3c) suggest a much higher overall reduction for a combined scenario.

The reason is that applying a certain measure to the stock, e.g. fewer cars, lowers the potential impact of the subsequent measures in the cascade, e.g. lower fuel consumption.

Especially for scenarios with many wedges, large relative variations of single parameters, or ambitious reduction targets the Bottom Line may be substantially higher than what would be expected by several disconnected *ceteris paribus* calculations (cf. also Pacala and Socolow[30]).

There is no bottom line of fuel consumption for gasoline driven cars because there is no agreement on the minimum functionality of such vehicles. Also, the notion of individual transport may change in the future and hence, there may be further potential for lowering the fleet average fuel consumption below 2.8 l/100 km. However, for vehicles that are both suitable for city driving and taking a family of four on a holiday, a global fleet average of less than 3 l/100km is an ambitious target. The future size of the car fleet and kilometrage could also be reduced below the current level of industrialized countries. All these reductions remain speculative however and lower the quality of life unless we *expand the system boundaries* to identify sustainable transport solutions in a larger context.

This can be done in several ways:

1. Lower the carbon intensity of fuel by introducing CCS and electric vehicles or a (partial) shift to biofuels.
2. Shift modes of transport to go beyond energy efficient individual transport
3. Compensate higher transport emissions with tougher goals in other sectors such as buildings and materials industry

1) 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. The authors find that 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[31] 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.

China-specific studies that determine large scale reduction impact and costs of these alternatives are still missing however; and one must bear in mind that other sectors may be dependent on these alternative energy sources as well to reach their carbon target.

2) The share of urban population in China increases rapidly and the difference in income between urban and rural population is substantial.[32] Cars that are mainly used within cities are likely to constitute a major share of the stock and in the face of urging climate change mitigation, 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 car ownership and kilometrage.[33-34] 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.[35]

3) Less substantial emission reductions could be allocated to passenger cars if other sectors can achieve stronger reductions. Next to transportation, buildings and industries are the two major contributors to energy-related carbon emissions (33% and 36%, respectively).[36]

There is much evidence for an emission reduction potential of at least 29 % within the building sector until 2030,[1] and some *passive houses* can save up to 90% compared to the present consumption.[37] The building sector therefore has – at least on paper – 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[36].

Both recycling and reuse of car parts will challenge waste management, especially if the quality of the various materials shall be maintained and 'down-cycling' shall be avoided.

The model presented allows for an 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 can help to forecast material quality issues in future recycling, potential resource scarcities especially for materials in electric vehicles, and a more comprehensive ecological footprint in the mid- and long-term horizon.

Supporting Information Available

We provide the complete system definition, the model approach, documentation of data sources, and additional results. This material is freely available via http://pubs.acs.org.

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TABLE:

Table 1. Sector target proposal for carbon emissions from the passenger car fleet in China, 2050, based on table 3.10 in IPCC AR4[1]. The right column shows the corresponding emission targets for China's passenger car fleet, assuming an even reduction for all sectors and a unitary global per capita emission quota in 2050. In 2000, global CO_2 emissions from passenger cars were about 2.4 Gt/yr[38] and the expected share of Chinese in the world population in 2050 is about 16 %.[21]

Class	**CO2 conc. at stabilization [ppm][1]**	**Global average temperature increase [°C][1]**	**Change in global CO_2 emissions 2000 → 2050 [%][1]**	**CO2 emission goal for global passenger car fleet [Gt CO2/y]**	**CO2 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

FIGURES AND CAPTIONS:

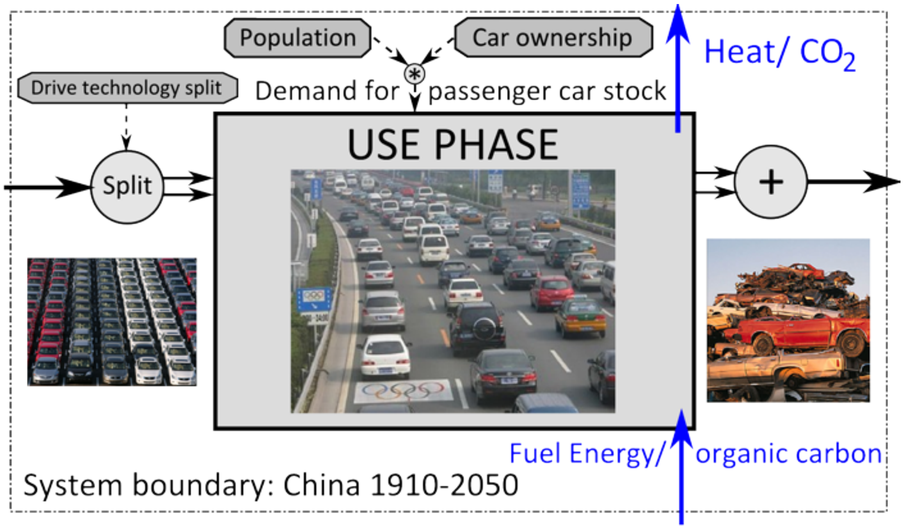

Figure 0. TOC Art

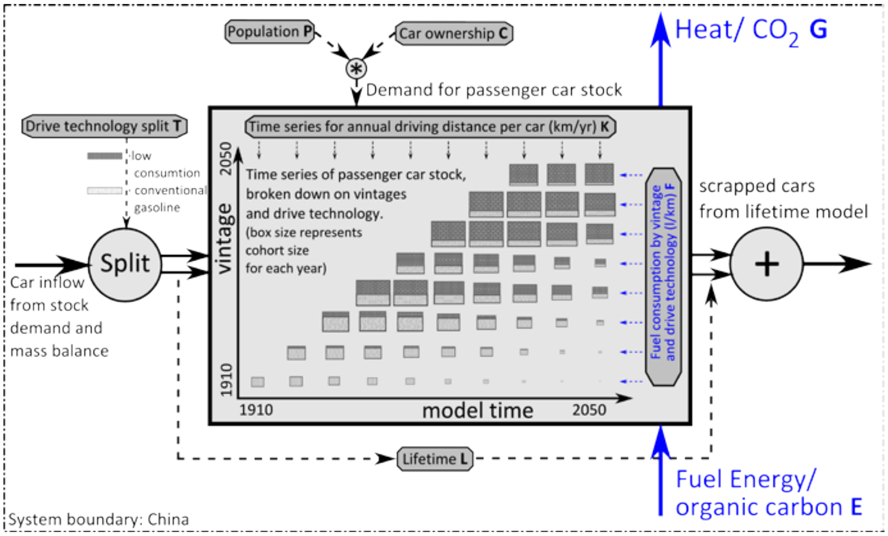

Figure 1. Dynamic model for stock and flows of material (Chinese passenger cars), energy (fossil fuel), and carbon emissions, 1910 to 2050

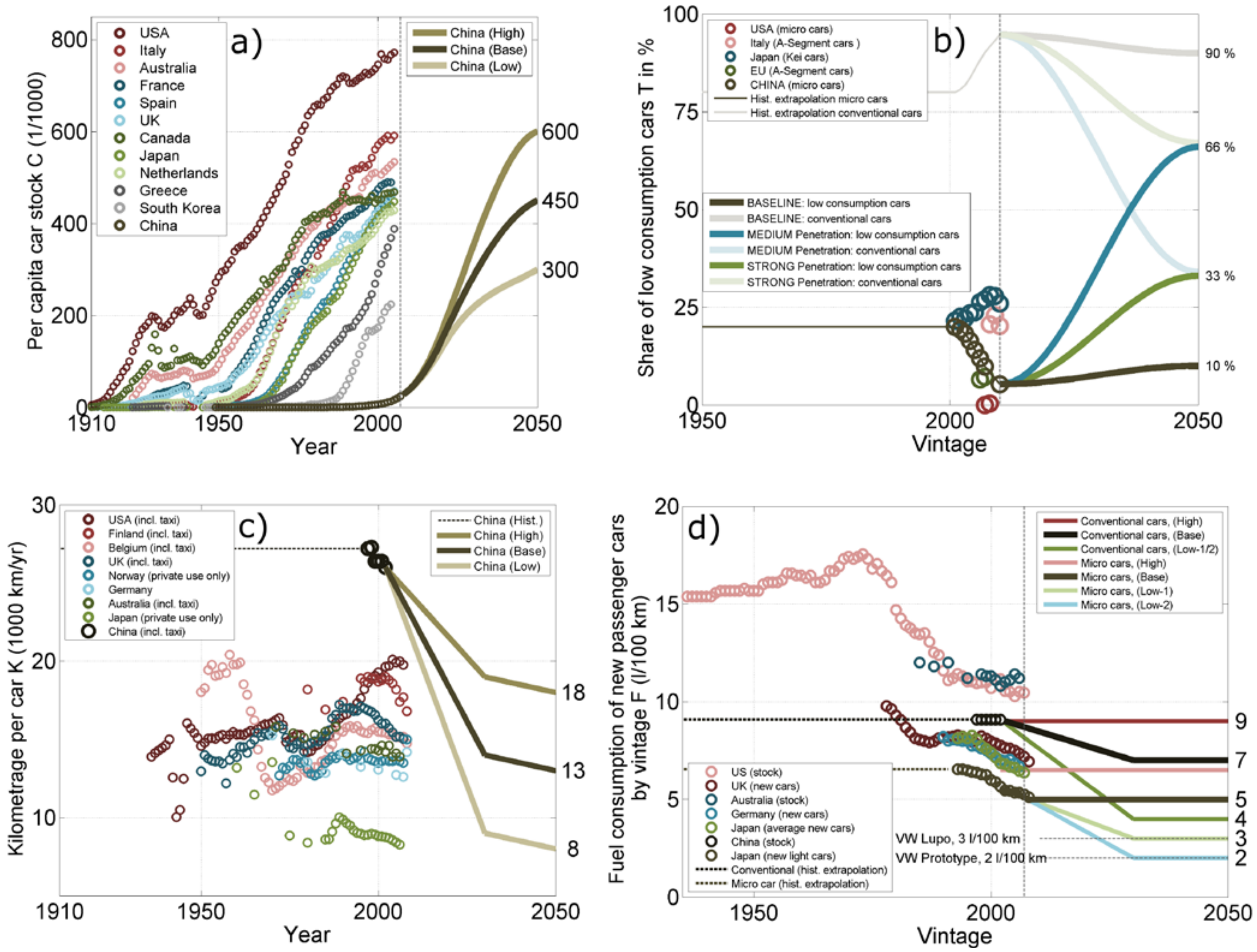

Figure 2. Historic data and future scenarios for cars per capita C (a), drive technology share T (b), annual kilometrage K (c), and fuel consumption per 100 km F (d).

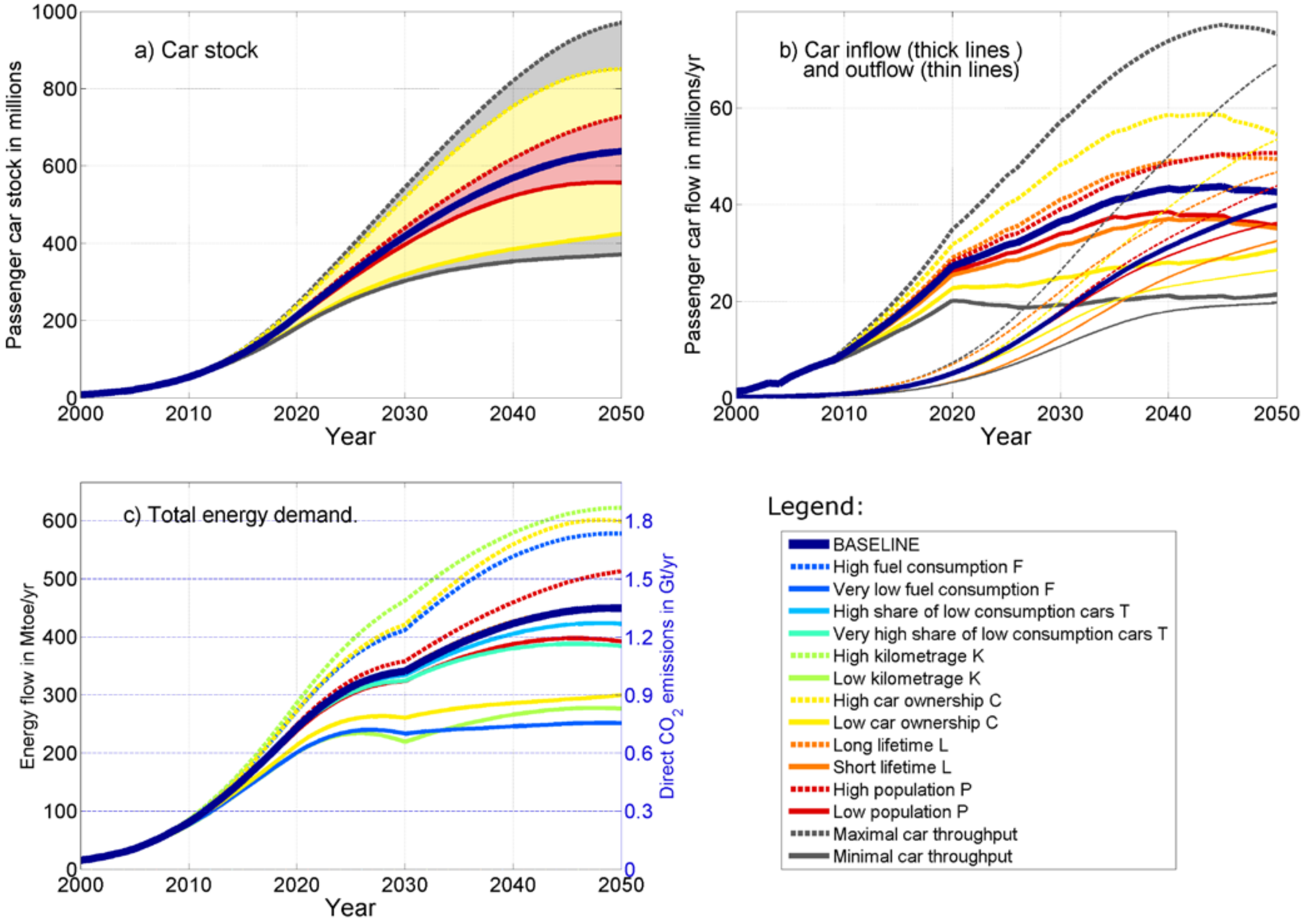

Figure 3. Absolute sensitivities with respect to changes in model parameters: Top row: car stock (a) and flows (b), second row (c): total energy demand and emissions.

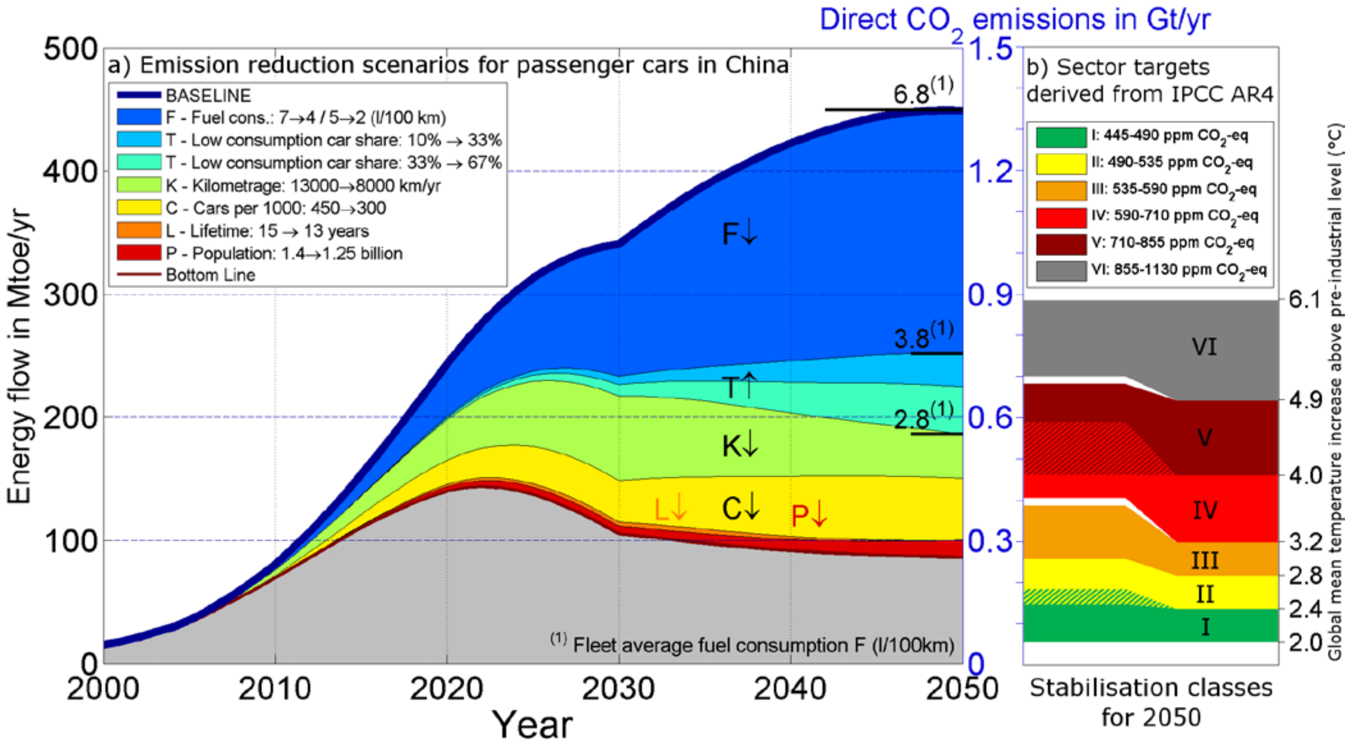

Figure 4. a) Wedge plot of direct energy consumption (left) and CO_2 emissions (right) for passenger cars in China. All six model parameters are successively changed from their base value to lower the energy throughput. b) Sector targets for carbon emissions (left) derived from the six classes of temperature increase in IPCC AR4 (right) assuming even contribution of all sectors and a uniform global per capita emission quota in 2050.