作品名称：Costs and potentials of reducing CO_2 emissions in China's transport sector: findings from an energy system analysis

作品类别：学术论文类

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Costs and potentials of reducing CO_2 emissions in China's transport sector: findings from an energy system analysis

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Abstract

To derive the cost-effective measures for CO_2 mitigation, this paper presented a MAC curve for Chinese transport sector considering the interlinkages between whole transport modes, policies, consumer preference, and other uncertainties. By employing the energy system model--TIMES, we visualize the marginal abatement cost curve for different scenarios to examine how carbon peak policy and consumer preference between conventional and alternative energy of plug-in hybrid vehicle drivers shape an energy-system wide MAC curve.

The results underline intercity passenger transport sector has the cost advantage of emission reduction and accounts for almost 45.4% of all CO_2 emissions mitigation in the baseline development. We find that although NEVs are applied in advance under the carbon peak policy shock, the increase of marginal costs of traditional techniques such as diesel buses makes the MAC curve shift to the right. The greater proportion of gasoline utilization of PHEV consumers makes the whole MAC curve shift to the right, which illustrates all kinds of transport modes costs increased. The results of this study show that MAC curves are robust to electricity price and the discount rate, the fuel price and the demand level were singled out as the most important influencing factors.

Key words

Marginal abatement curve; Transport sector; TIMES model; Carbon peak policy

1. Introduction

In 2015, transport sector accounted for approximately 9.3% of energy-related CO_2 emissions in China (International Energy Agency, 2017), indicating that the transport sector plays an important role in China's entire CO_2 emission process. In June 2015, China submitted a document to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat and made a commitment to achieve the carbon emission peak around 2030 (NDRC, 2009). In the past few years, the demand of China's transport sector has experienced a sharp increase, especially private vehicle stocks increase by 212.75% compared to 2010 (NBSC, 2018). The continuing increase of energy terminal consumption by rising transport demands would pose extra challenge for realizing China's national carbon emission reduction target.

Furthermore, China's wobbly transport policies are not conducive to meeting its emissions-reduction targets. For example, Chinese government announced "Energy Conservation and Development Plan of New Energy Automobile Industry (2012-2020)" in 2012 and stipulated that battery electric vehicle (BEV), plug-in hybrid electricity vehicle (PHEV) and fuel cell electric vehicle (FCEV) are new energy vehicle (NEV) types in China. PHEVs were treated as the transition from fossil fuel to electrification of the transport sector and the private individuals who purchased a PHEV could get government subsidies. In 2018, NDRC of China considered PHEVs as one kind of fuel vehicles in Regulations on Investment Management of Automobile Industry (Draft for Comments). The attitude of China's government towards the positioning of PHEVs is ambiguous, it is harmful for integral strategy implementation of China's transport sector. Therefore, it is necessary to study how to reduce emissions efficiently and give a least cost pathway of transport sector.

Chinese government is paying close attention to looking forward to affordable means of reducing carbon emissions, such as energy efficiency improvement, low carbon technology development, demand side management, etc. Adopting low-carbon technologies is a promising choice to achieve energy conservation and carbon emission reduction, which often requires additional costs for research and development. From the perspective of cost benefit, the marginal CO_2 emission abatement cost, which calculates additional cost of per unit of CO_2 emission reduction, is an effective index to evaluate the competitiveness of low-carbon technology. Marginal abatement cost (MAC) curves, as graphical representations of the relationship between abatement costs and emission (or emission reduction) level, have become a tool to determine the appropriate set of measures to reach the desired carbon reduction target (Tomaschek J, 2015). MAC curves were subdivided into many forms, they may differ in terms of area, time range and generation method. In terms of generation method, MAC curves were mainly divided into two types, i.e. "expert based MAC curves" and "model export MAC curves".

This paper will demonstrate how to derive MAC curves for Chinese transport sector with a multi-stage optimization energy system model, TIMES (The Integrated MARKAL-EFOM System) model, considering the substitution effects of different options. Firstly, we will create China's energy provision chain of transport sector from 2010 to 2050 though TIMES model, to get additional technology capacity and carbon emissions in every 5-year period. Secondly, by imposing gradually higher carbon taxes step by step and recording the quantity of emission reduction, we will deduce the model export MAC curves. Thirdly, using scenario analysis, we plan to explore the impacts of CO_2 emissions peak policy, consumer preference, technology issues, fuel price and final demand on MAC curve. It is significant that the final MAC curves provide reference for future low-carbon energy development strategies.

The paper is structured as follows: Section 2 presents recent studies covering MAC curves which are generated by two methods and TIMES model in detail. Section 3.1 presents the basic framework of the TIMES model and its structure as well as technology detail in transport sector and in the fuel provision sector. Section 3.2 shows how MAC curves can be derived which incorporate fuel provision, interdependencies and interlinkages between options, and substitution effects between options. Section 4 shows the definition of different scenarios. Section 5 presents the results of the model application and shows how to mitigate end-use related carbon emissions of transport sector in China. Concluding remarks and policy implications are given in Section 6.

2. Literature review

There are mainly two kinds of MAC curves, one is expert oriented while the other is model oriented. Expert-based MAC curves give information on how much GHG could be saved if the measure was used at his technical maximum (Vogt-Schilb and Hallegatte, 2014) (参考文献). It is calculated based on a reference technology, considering the carbon intensity and imperfect substitutability of different technologies (Vogt-Schilb and Hallegatte, 2014). In other words, the expert-based MAC curves show the rank of the costs of different measures to achieve incremental levels of emissions reduction (Naucler et al. 2009), so expert oriented MAC curves are discrete. The advantage of expert-based abatement cost curves is that the marginal costs and the abatement potential can be precisely distributed to one low-carbon technology, so it can be understood by policy makers easily (Kesicki, 2013a). However, reference technology is set subjectively in this method, the whole MAC curve is influenced by it easily. And expert oriented MAC curves do not take into account any dynamic changes, technological lock-in and lacks the research on the interconnection and interdependence within the energy system.

There are some existing literature graphed expert-based MAC curves in country scale, the most representative one is McKinsey's MAC curves from a global perspective (Enkvist et al., 2007). And more authors focus on the expert-based carbon emission cost issues in a specific sector of a country or region, especially in some high carbon intensity industry sectors like cement and steel. Worrell et al. (2000) constructed an energy conservation supply curve for the US cement industry in 1994 and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for 30 cement measures. Brunke and Blesl (2014) assessed the energy conservation and CO_2 abatement potential of 21 identified German cement measures by deriving fuel, electricity conservation and CO_2 abatement cost curves. Hassenberigi (2013a, 2013b) built the expert-based MAC curves of China's cement industry and China's steel industry successively. For transport sector, Peng et al. (2018) estimated carbon dioxide abatement costs of energy-saving technologies for passenger cars in China. From the research above, we find that authors obtained the expert-based MAC curves while they know each step of daily operation and production of a specific sector. It would be a difficult work to calculate the expert-based MAC curves of multiple departments in the nation economic system because of the strict data requirements.

Model export MAC curves, differing from expert-based MAC curves, are driven by energy system models. The advantage of model export MAC curves is concerning about the interactions via energy structure and market conditions under cost minimization. The model export MAC curves could be generated by either top-down or bottom-up models. They are both generated by imposing progressively stricter constraints on allowed carbon emissions within the models or by introducing progressively higher carbon taxes on the system (Kesicki, 2013a).

MAC curves generated by top-down models lack of technological detail in the graphical representation and rely on historic data for the calculation of future abatement costs (Kesicki, 2013a). Most of research use CGE (Computational General Equilibrium model, CGE model) model to establish MAC curves (Klepper and Peterson, 2006; Qian et al., 2017), and some use input-output analysis (Xia and Fan, 2012).

MAC curves generated by bottom-up models include technology investment costs and fixed costs in the energy system, do not present detailed technological measures cost in the abatement curve (Kesicki, 2013a). Marginal abatement costs can be diluted by other constraints. TIMES model used in this research was one of the most common bottom-up methods to build MAC curves. Chen (2005) calculated nation-wide mitigating carbon emissions costs during the period 2000–2050 of China by MARKAL-MACRO model and simulated impacts of carbon emission abatement on GDP. Kesicki (2012a) combined UK MARKAL model with decomposition analysis to create MAC curves for the UK residential sector. Then he addressed the influence of extreme fossil fuel price changes, choice of the discount rate, the availability of key abatement technologies and the demand level on sensitivity of MAC curves (Kesicki, 2013b). Besides, there are some research of carbon emissions by TIMES model focusing on transport sector. Kesicki (2012b) used UK MARKAL to derive mitigation costs and emissions reduction potentials in the UK road transport sector. He simulated different carbon tax implemented paths and discount rates to illustrate the influence of path dependency and types of discount rate on MAC curve. Differently, Tomaschek (2015) drew a MAC curve for transport sector by energy system model generator TIMES for South Africa (TIMES-GEECO). This model concentrates on deriving the whole well-to-wheel GHG emissions by considering the tank-to-wheel emissions (i.e. vehicle emission intensity,) and well-to-tank emissions (i.e. emission intensity of fuel provision)..

The research for model export MAC curves of transport sector has some common points, one is about the research scope, they mainly focus on the road transport; the other is that some small land surface countries like UK and South Africa were paid more attention. In this kind of countries, road transport could carry most of the passengers and goods because they don't need to be transported in long distance. The characteristic of Chinese transport sector is different from these countries completely. First, China is an industrialized country, freight transport accounts to a great proportion of total transportation, especially the application in some large-scale public transport modes like ships and trains. Second, long distance passenger transport (intercity) is general for Chinese transport sector, too. The links between different regions of China is tight, people are able to travel for business or pleasure among different provinces, so aviation and trains have developed rapidly in the last decade. Our research demonstrates MAC curves of Chinese transport sector with TIMES model and the research scope could be expanded for whole transport modes (road, railway, water and air modes for passenger and freight transport). We have further evolved the transportation sector into three sub-sectors, urban passenger transport, intercity passenger transport and freight transport sectors. Thus, we'd like to answer questions like: what's the CO_2 reduction roadmap for China's transport sector like considering policy interactions and variety of technology that almost covered all trip modes? How the burden of carbon emission mitigation should be spread among urban passenger transport, intercity passenger transport and freight transport sectors?

Besides the common factors in TIMES study like discount rate, fuel price and demand level, we also explored the impacts of some factors which are unique to China on MAC curve, such as the carbon peaking policy and consumer preference between conventional and alternative energy of PHEV drivers. In that way, we could get CO_2 reduction pathway under target of carbon peaking for China's transport sector and develop a unified PHEV development strategy for the Chinese government.

3. Methodology

3.1 Energy system modelling

The TIMES (The Integrated MARKAL-EFOM System) model is a dynamic, technology-based linear programming energy system model which developed within the Energy Technology Systems Analysis Program (ETSAP) of IEA. The TIMES model describes the entire energy system from primary energy supply, energy conversion, to transport, industry, residential and commercial end-use sectors. In TIMES the objective is to minimize the total discounted system costs when demand for each type of end use of energy is satisfied (see Eq. (1)) (Selosse and Ricci, 2014).

$$\mathrm{NPV} = \sum_{r=1}^{R} \sum_{y \in years} (1 + d_{r,y})^{refy-y} \times ANNcost(r,y) \quad (1)$$

where *NPV* is the net present value of the total cost; *ANNcost (r,y)* is the total annual cost in region *r* and year *y*; $d_{r,y}$ is the discount rate (A 5% discount rate is applied in our model), *refy* is the reference year for discounting, *years* is the set of years and *R* the set of regions. Several parts consist of the total annual cost (*ANNcost*), mainly including technology investment costs, energy import costs and energy export revenue, annual fixed costs and maintenance costs when each unit of capacity operates. According to different research purpose, there are other costs that are taken into account into the *ANNcost*. For example, taxes and subsidies associated with commodity flows, process activities or investments, the variable operational costs which depended on the activity (production level) of a process, as well as those dependent on flow costs of commodities (e.g., CO_2 transport, delivery costs) (Tomaschek, 2015), residual monetary value of all the investments remaining at the end of the modeling horizon and emissions costs when the user specifies a cost per ton of emissions (Mathur et al., 2003; Liu et al., 2018).

Concerning some adaptable constraints and assumptions, TIMES will describe the structure of energy system. Then the model forecasts fuel choice (e.g. oil, gas input), energy technologies pathway (e.g. production level, newly installed capacity) and CO_2 emissions under different policies being implemented for now or in the future. Obviously, the strengths of TIMES representation of transport sector include the technological detail and taking account of system-wide interactions via traditional fossil energy and renewable energy like hydrogen. The results of TIMES model will help policymakers determine how to choose and develop effective low-carbon technologies to cut down total carbon emissions of China's transport sector.

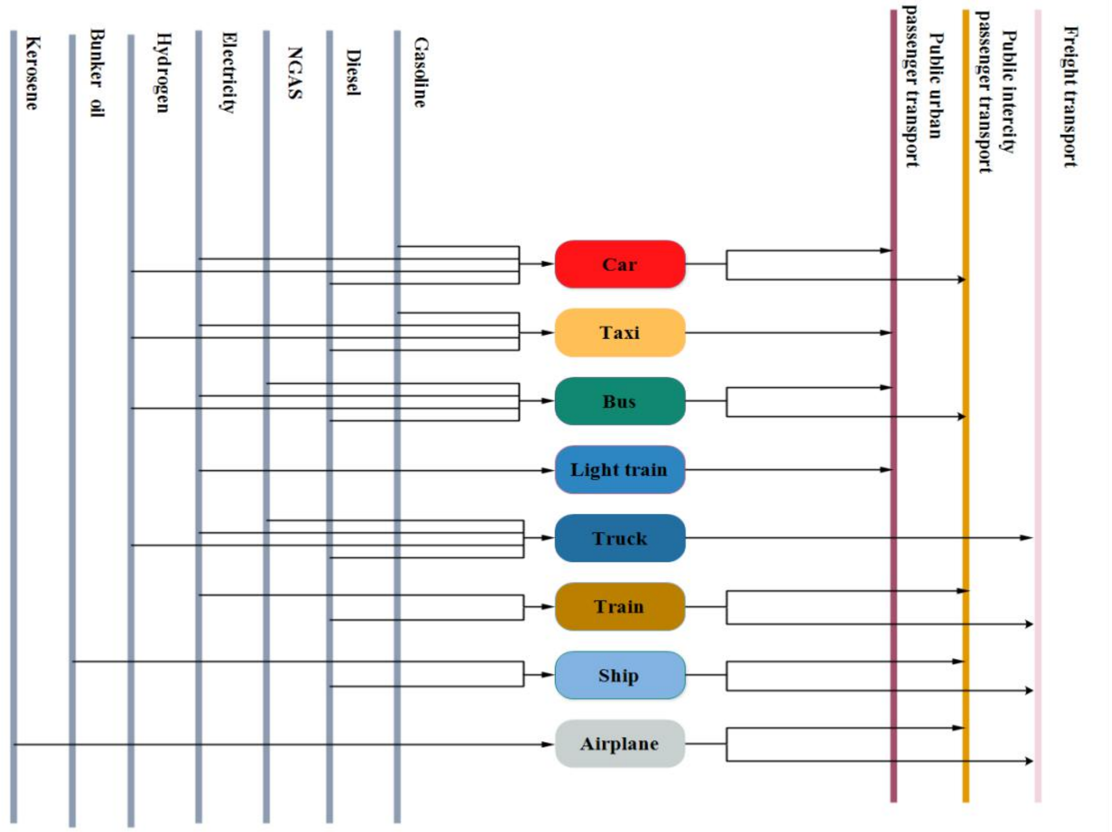

Fig.1. Brief reference energy system of China's transport sector

For China's transport sector, we built a TIMES model with three sub-sectors, including intercity passenger transport sector, urban passenger transport sector and freight sector, as illustrated in Fig.1. In this context, the passenger transport sector is subdivided into urban and intercity passenger transport sector to distinguish long or short transport distance (Tomaschek J, 2015). The former consists of individual passenger transport such as car and public urban passenger transport like taxi, bus and light train (subway); the latter includes such as car, bus, railway, train, ship and plane. The freight transport sector includes almost all transport modes like truck, railway, train, ship and plane. Finally, we obtained total 43 technologies for the three sub-sectors to meet the demand (Table S1).

Transportation services demands are the main exogenous variables in TIMES model, it is usually expressed in billion passenger kilometer and billion ton kilometer. Transportation services demands are defined for three sub-sectors in this paper, from 2010 to 2050 with the interval of five-year period. Future travel demands mainly refer to a Fuel Economy and Environmental Impacts (FEEI) model which concerned about the income-level basis, car purchase prices, separated sales into purchases for fleet growth and for replacements of scrapped vehicles, and examined various possible vehicle scrappage patterns for China (Huo and Wang, 2012).

For each sub-sector, their technologies compete to meet their own exogenous transport demand. The substitution between technologies is completely based on the total costs: the TIMES model seeks a combination of technologies that are characterized by the lowest investment and fixed costs while meeting the constraints of the transport model. In this paper, the infrastructure constraints are defined for 43 technologies (e.g. availability of subway due to metro planning in

12th five-year plan) to avoid the limitless expansion of some cheap technologies. Carbon emission constraints are applied to the specific scenario to ensure peak carbon emission in 2030.

4. Assumptions and scenarios

This paper does not only present the results for the reference case and a policy scenario but varies key assumption in 8 scenarios in order to assess how technology issues, discount rate, fuel price and demand level influence the shape and structure of MAC curve of China’s transport sector (see Table 1). The sensitivity analysis helps to get results about the robustness of the MAC curves.

We impose progressively higher carbon taxes from 0 to 500$\$_{2010}$/t and record the quantity of abated emissions to deduce MAC curves by 28 runs. The carbon tax increases by discount rate of 5% p.a in the REF scenario from 2020 to 2050 so that it represents the same cost in the model optimisation throughout the entire model horizon (Kesicki, 2013b). All costs are given in 2010 values. With the commitment of 2030 emission peak goal, this study explores the effects of carbon peak policy on MAC curve in China’s transport sector, so we focus on the year 2030 as an important medium-term emissions reduction target.

Two scenarios concern the consumer preference issues of PHEVs. PHEVs allow drivers to choose actively the fuel their vehicles operate on, in the PHEV2 scenario the demand ratio between electricity and gasoline of PHEVs is 2:8, while the ratio is 8:2 in PHEV8 scenario.

The sensitivity analysis is carried out in this study to evaluate the most influencing factors for MAC curve. The HDR scenario and LDR scenario explores the effects of different discount rate level on MAC curve. In FFP scenario, the prices of gasoline, diesel, bunker oil, kerosene and natural gas are increased by 200% because of the fossil fuel depletion, while the price of electricity is decreased by 25% with the great adoption of renewable energy in EFP scenario. The DEM+ scenario studies the impact of higher demand level, while the DEM- scenario analyses the consequences of lower demand level.

Table 1
Overview of scenarios

Scenario	Category	Description
REF	Reference case	Carbon tax increase by 5% p.a. from 2020
CEP	Policy	China achieve CO_2 emissions peak by 2030
PHEV2	Consumer preference	Demand ratio between electricity and gasoline of PHEVs is 2:8
PHEV8	Consumer preference	Demand ratio between electricity and gasoline of PHEVs is 8:2
FFP	Fuel price	Costs for gasoline, diesel, bunker oil, kerosene and natural gas increased by 200%
EFP	Fuel price	Costs for electricity decreased by 25%
HDR	Discount rate	Discount rate rose to 7%, all hurdle rates, taxes and subsidies removed
LDR	Discount rate	Discount rate lowered to 3%, all hurdle rates, taxes and subsidies removed
DEM+	Demand level	All energy service demands increased by 10%
DEM-	Demand level	All energy service demands decreased by 10%

5. Results and discussion

5.1 System-wide MAC curve

We calibrated the model results of vehicle stocks and energy consumption with historical statistics (NBSC, 2011, 2016). We made comparison of each vehicle's stocks in 2010 and 2015 and find the deviations of vehicle stocks are 4.0% and 1.3%, respectively. The deviation of different types of energy consumption in 2010 is 0.74%, which is 1.0% in 2015. All deviations are lower than 5%, making the model results convincing.

Fig. 2 represents a MAC curve in the REF scenario for the whole transport sector in 2030. The height of each bar represents the marginal abatement cost, and the width represents the emission abatement and the color indicates the sub-sector. Model results indicate that total energy-related CO_2 emissions are 1572 Mt CO_2 in 2030 without any CO_2 policy, which compares to 427 Mt CO_2 in 2010 and 501 Mt CO_2 in 2015.

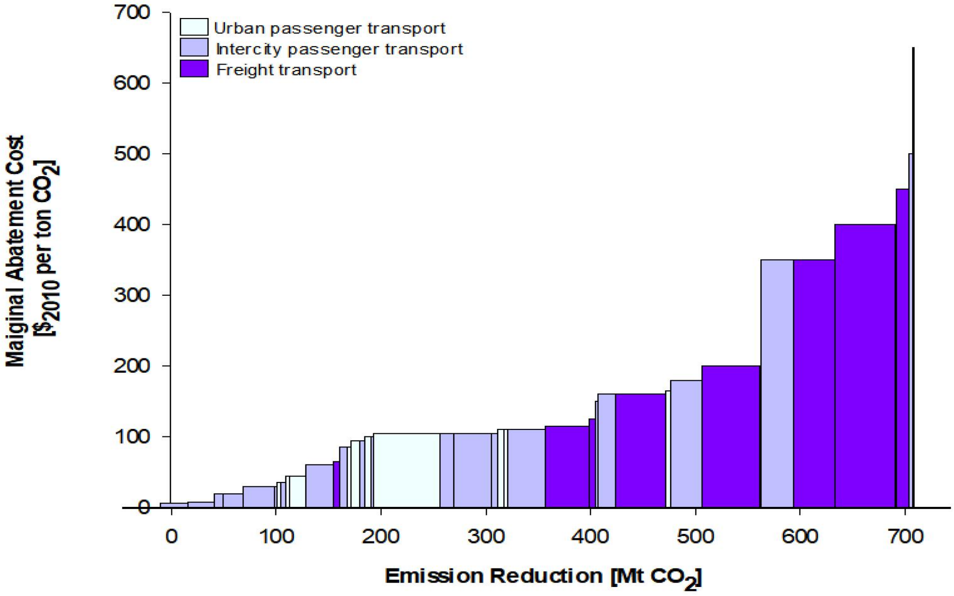

Fig. 2. MAC curve for the transport sector of China in 2030

In the model run with the highest implemented CO_2 tax of \$650/t CO_2 in 2030, 709 Mt CO_2 are abated, reducing emissions to 863 Mt CO_2. This corresponds to an emission reduction of 63% compared to the no-tax model run. Most of the low-cost abatement potential can be found in the intercity passenger transport sector (long-distance), which accounts for almost 45.4% of all CO_2 emissions mitigation in the baseline development. It is apparent that there are some low-cost abatement options in urban passenger transport sector (short-distance), but it just contributes 16.5% of CO_2 emissions mitigation. Freight transport sector have huge potentials of reducing CO_2 emissions, but the contribution of it is mainly dominant from around \$115/t CO_2 upwards.

Urban passenger transport sector includes a few types of road transport modes such as car, bus and subway, there is only a narrow gap among their energy efficiency. Hence the substitution between them could only reduce a small quantity of CO_2. As for intercity passenger transport sector and freight transport sector, in addition to the road traffic modes, there are also aviation, water transportation and railway transport. The emission mitigation caused by the substitution between them and road transport modes is huge, so the total emission reduction potential of these two sub-sectors are higher than urban passenger transport sector. Freight transport sector costs more per ton of goods on average than passenger transportation, so it spends more on emission mitigation overall.

5.2 Technology-wide MAC curve: reference scenario

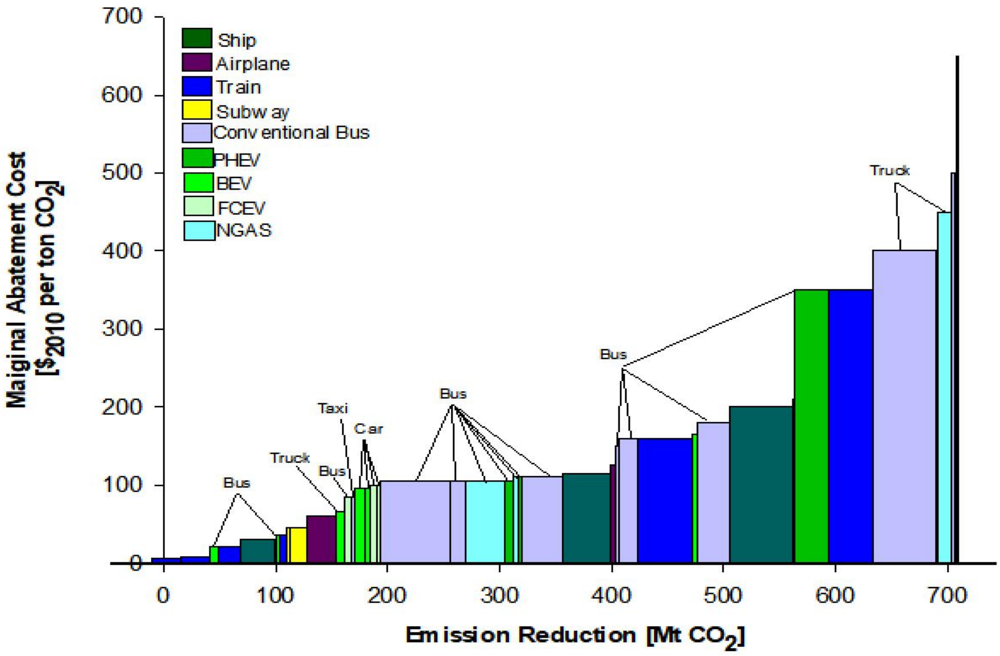

Fig. 3. Transport MAC curve for the REF scenario in 2030

The reference (REF) scenario describes a development of carbon emissions reduction with the standard assumptions of the China transport TIMES model. Specific technology choices for 2030 emission reduction are presented in Fig.3.

At the lower end of the MAC curve, the predominant trend in the intercity passenger transport is the promotion of public large-scale transport modes. At moderate marginal abatement costs of <65 \$/t CO_2, large shares of public vehicle activity are attributed to electricity-train (6\$/t CO_2), diesel-train (30\$/t CO_2), subway (45\$/t CO_2) and airplane (45\$/t CO_2). Two kinds of train provide almost 97 Mt CO_2 mitigation among these transport modes. Although the total investment costs of these large-scale transport modes are large, they are more economy and energy efficient per capita because of their large passenger flow volume. At moderate marginal abatement costs of 85-100\$/t CO_2, the cheapest option to reduce transport emissions is the switch from conventional gasoline cars towards BEVs and FCEVs as they don't product any carbon emission no matter in urban (short-distance) or intercity (long-distance) passenger transport sector.

In a range from 105 \$/t CO_2 to 350 \$/t CO_2, different kinds of buses begin to replace conventional gasoline cars. Firstly, conventional diesel buses reduce by 162 Mt CO_2 which is the most efficient kind of vehicle. Secondly, there is a trend concerning buses begin to consume electricity and natural gas. Plug-in electric buses and natural gas buses contribute to almost 82 Mt CO_2 reduction. Furthermore, the application of diesel-ship (160-350\$/t CO_2), diesel-train (160\$/t CO_2) and electricity-train (350\$/t CO_2) in freight sector decreased large quantity of CO_2 emissions. We can see that the trend of using large-scale transport modes are suitable for freight sector too as goods that transported by them are in large scale and take less time.

At the upper end of the calculated MAC curve (>400\$/t CO_2), electrification is intensified with applying fuel cell electric vehicle and plug-in hybrid electric vehicles for trucks, and natural gas buses also contribute to 12 Mt CO_2 reduction.

Overall, the most effective carbon emission mitigation path of Chinese transport sector is promoting the development of public transport modes in the early, then Chinese government should encourage people to buy new energy vehicles replacing conventional gasoline or diesel vehicles. China still has great potentials to expand the scale of public transportation, because even if the conventional buses are efficient and consume less fuel than conventional gasoline cars.

There is another interesting trend shown in the MAC curve that plug-in hybrid electricity vehicles (PHEV) for no matter cars, bus or trucks cost more than battery electric vehicles while the investment cost of PHEV is less than BEVs. PHEV is one kind of multifuel vehicles (MFV), they allow drivers to choose actively the fuel their vehicles operate on, and thus they might operate solely using fossil fuels. Cristian (2018) questions the cost-effectiveness of programs to incentivize the purchase of MFVs that ignore the fuel choice dimension and highlight the importance of accounting for fuel choice in the analysis of public policy and emerging technologies. He finds when the energy-adjusted alternative fuel–conventional fuel price ratio is 0.9, normalized demands for two kinds of fuels are the same. The actual value of energy-adjusted electricity–gasoline price ratio of China is around 0.9 from 2010 to 2015. For this reason, we created the assumption that the PHEV drivers use electricity and gasoline equally in this paper. As carbon tax increases, PHEVs produce CO_2 so the total costs of PHEVs are higher than that of BEVs and FCEVs. Section 5.4 presents the results of the PHEV scenarios and shows how the substitution patterns between gasoline and electricity influence the structure of MAC curves.

5.3 Carbon peak policy

This section analyses the impact of carbon peak policy on the transport MAC curve. The CEP scenario discusses the assumption of carbon emission of China's transport sector peaking in 2030. We defined the constraints that limited the carbon emissions in 2035-2050 to be less than 1572Mt, as well as the carbon emission of REF scenario in 2030 from TIMES model.

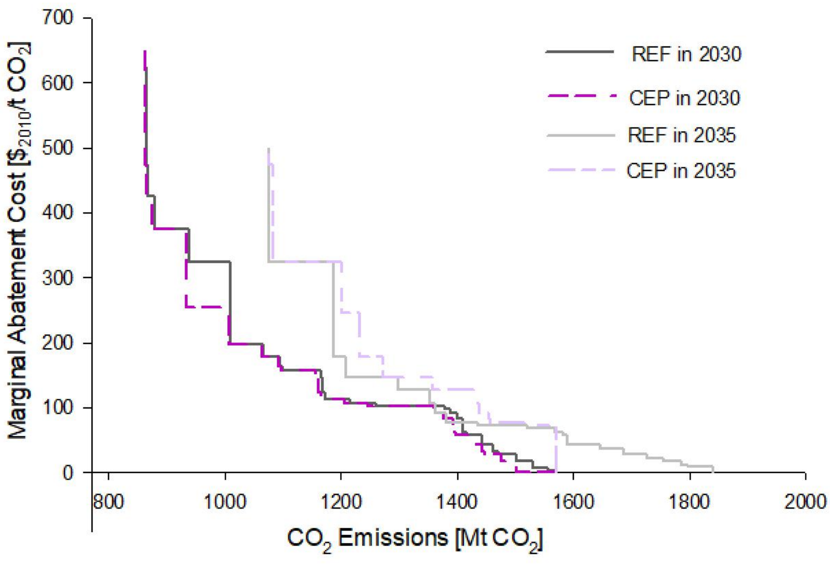

Fig. 4. MAC curve for the REF and CEP scenario in 2030 and 2035

The MAC curve of 2030 for carbon peak scenarios (Fig. 4) reveals that the difference between the scenarios is rather limited with an exception in the range from \$1/t CO_2 to \$7/t CO_2. While, for the range from \$260/t CO_2 to \$350/t CO_2, the abatement potential varies a little more. The carbon emission of the CEP scenario without tax is equal to the extent in REF scenario in 2030. The results confirm that the MAC curve is relatively robust to the limitation on carbon emission in peak year. The details in technology roadmap of transport sector for CEP scenario in 2030 (Fig. 5a) show that the overall MAC curve looks very similar to the REF scenario up to $7/t CO_2. At the lower end of the MAC curve in CEP scenario, the application of ships, natural gas buses, diesel train and plug-in hybrid electricity trucks are the first technology combination to reduce CO_2 in REF scenario from $1/t CO_2, while the transport sector begins to reduce CO_2 at the cost level of $6/t CO_2 by promoting use of electricity-train. Plug-in hybrid electricity buses and taxis are replaced by conventional diesel buses and bunk oil ship at a cost level of $260/t CO_2, thus at $350/t CO_2 less than the REF scenario.

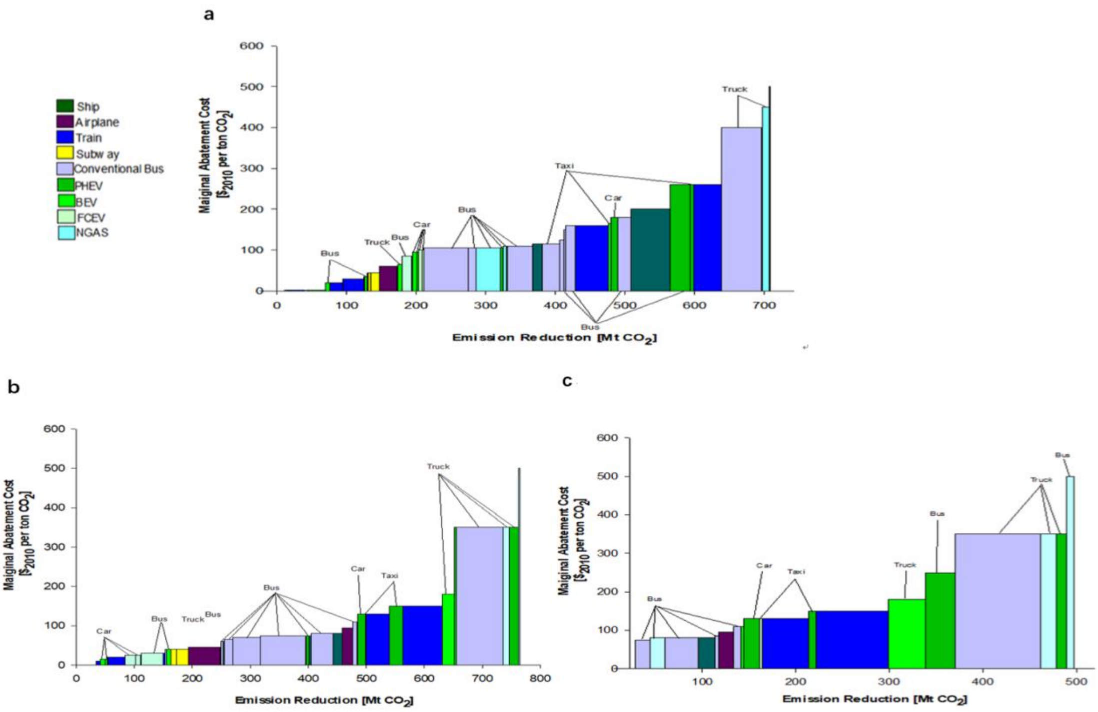

Fig. 5. CEP scenario related MAC curves| a, Transport MAC curve for the CEP scenario in 2030. **b**, Transport MAC curve for the REF scenario in 2035. **c**, Transport MAC curve for the CEP scenario in 2035.

Fig. 4 also shows the MAC curves for CEP and REF scenario in 2035 after the peaking of carbon emission in the TIMES model. In the REF scenario, the transportation sector could generate totally 1839.661 tons of CO_2 in 2035. We compared CEP and REF scenarios and found that in order to achieve the carbon peaking, the internal structure of the transportation sector was optimized before the cost level of $75 in TIMES model, so as to make the carbon emission level of transportation sector be equal to that in 2030 to ensure peaking in 2030, only 1572 tons of CO_2. The MAC curves both stop abating emissions when it reaches 1075 tons of CO_2. CEP scenario does not change any technology-related endogenous variables in the TIMES model, so the emission endpoints of MAC curve in CEP scenario and REF scenario are the same. In the range of $75/ton-$500/ton CO_2, there is an average emission reduction of 1.4 tons less than that of REF scenario under the same cost level. Besides, carbon peaking will be achieved in 2040, 2045 and 2050 under the cost levels of 70, 70 and 60 respectively. It means if the carbon tax policy were imposed on the transport sector, a tax level of $60-$75 would be sufficient to help the transport sector reach its carbon peak.

Fig. 5b and Fig. 5c show the technology-wide MAC curves for the REF scenario and CEP scenario in 2035. At a cost level larger than $75, the carbon reduction pathway of two scenarios is roughly the same. In the context of the CEP scenario, the carbon emissions reduction potential of the traditional diesel bus declined compared to REF scenario, while BEVs and PHEVs become more effective, their potentials increase about 9 tons and 20 tons of CO_2 respectively. Due to that the cost of traditional abatement techniques such as diesel buses increases in CEP scenario, the MAC curve moves to the right in Fig. 4. But NEVs become more effective in CEP scenario, the whole curve finally went back to the original level under the cost level of $330. It can be seen that if the carbon peak aims to be achieved before 2030, the transportation sector needs to achieve substantial emission reduction after 2030, and NEVs should play a more important role in it.

5.4 Technology issues of PHEV

The PHEVs allow drivers to choose actively the fuel their vehicles operate on, and thus the way they might choose fuel not only according to the price of fuels, but also their consumption preferences. Therefore, two scenarios are presented in this scenario to show how different consumption preference of PHEV drivers influence MAC curves. The normalized demands for electricity in the PHEV2 scenario and PHEV8 scenario represent the energy-adjusted alternative fuel–conventional fuel price ratio of 1.15 and 0.8, respectively (Cristian, 2018).The picture looks very different for the PHEV2 and PHEV8 scenarios (Fig. 6) compared with REF scenario. The MAC curve of PHEV2 scenario is substantially more expensive compared with the REF scenario while their CO_2 reduction potentials are basically the same. Plug-in hybrid electricity vehicles are utilized in buses, cars, taxis and trucks at cost level of $160, $270, $290 and $700 respectively much more than the REF scenario (Fig. 7a). The application of all types of PHEVs reduced 33 Mt CO_2 in PHEV2 scenario totally, and plug-in hybrid electricity buses account for about 90% of it. The greater proportion of gasoline utilization of PHEV consumers makes the whole MAC curve shift to the right, which illustrates all kinds of transport modes costs increased.

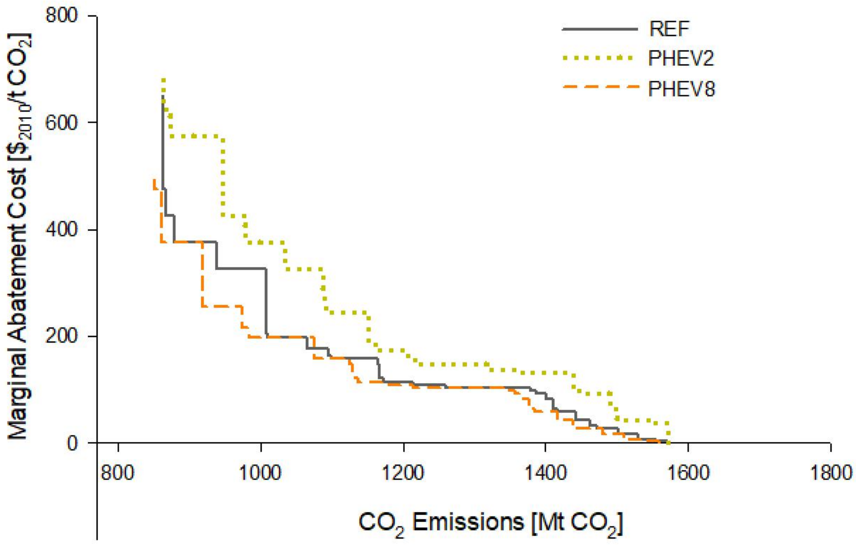

Fig. 6. MAC curve for the REF, PHEV2 and PHEV8 scenario in 2030

As for PHEV8 scenario, the technology path of carbon mitigation is similar to the REF. The difference in emissions between PHEV8 scenario and the REF scenario is on average 31 Mt CO_2 for a given tax level, while this difference increases slightly with rising carbon prices. The application of PHEVs reduced 37 Mt CO_2 in PHEV8 scenario totally, and 12% more than PHEV2 scenario.

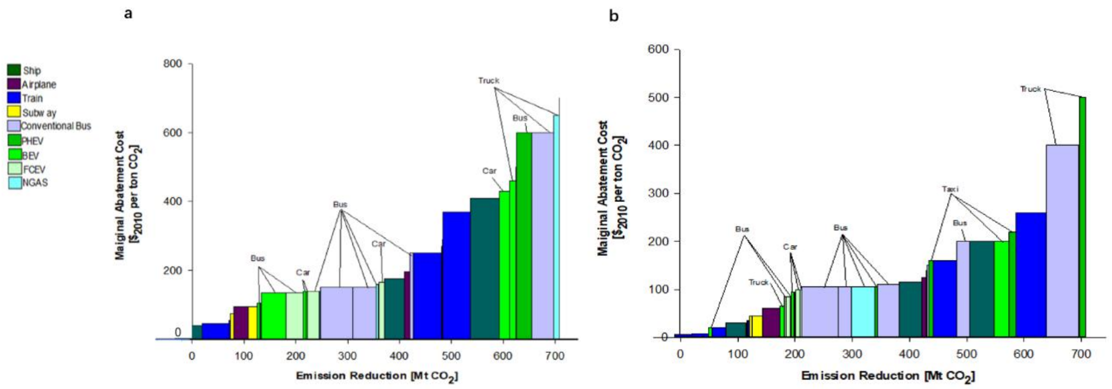

Fig. 7. PHEV related MAC curves| a, Transport MAC curve for the PHEV2 scenario in 2030. **b**, Transport MAC curve for the PHEV8 scenario in 2035.

PHEVs is an important kind of transport technologies as the transition from fossil fuel to electrification and the government is promoting them to the public. The preference of gasoline will produce more CO_2 with the expansion in capacity of PHEVs, the TIMES system need to choose some expensive technologies earlier to minimize the total costs as the carbon taxes are increasing. Hence, the consumption preference of PHEV drivers influences the costs and potentials of other technologies in MAC curves directly. The higher ratio of electricity using for PHEVs drivers would help transport sector to reduce CO_2 much more and faster.

Chinese government might not satisfy with the effects of CO_2 abatement of PHEVs so tried to treat them as one kind of fuel vehicles, but the policy has not been implemented formally until now. This paper proves that PHEVs are cost-effective and could help to reduce more CO_2 if the drivers prefer to using the electricity power system. The government should promote infrastructure construction and encourage car companies to increase battery capacity to guide PHEV drivers using electricity.

5.5 Fuel price

In the FFP scenario, the fossil fuel prices are increased by 200% over the whole first half of the 21st century, equivalent to long-lasting supply shocks seen in the 1970s (Kesicki, 2013b). In the EFP scenario, the electricity price alone is reduced by 25%. This represents a scenario of continuously low electricity prices, due to the popularization of some cost-effective renewable energy power like wind and photovoltaic. While the electricity price is about 92% of the gasoline price on an energy-equivalent basis in the REF scenario, it is only 69% in the EFP scenario.

Previous academic research has come up with an answer, which indicates that fuel price differences are overshadowed by existing tax levels and increasing CO_2 tax levels (Kesicki, 2013b). This hypothesis is challenged by looking at our two different fuel price scenarios in Fig. 8.

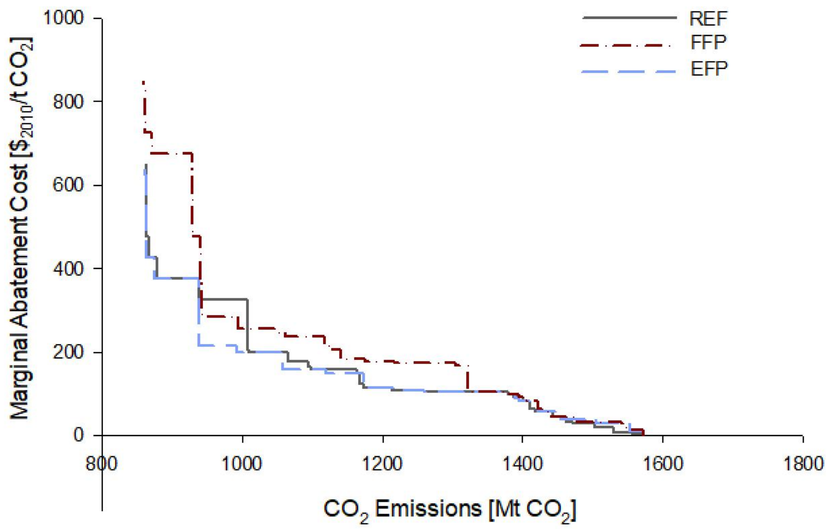

Fig. 8. MAC curve for the REF, FFP and EFP scenario in 2030

The MAC curve for EFP and REF scenarios reveals that the difference between the scenarios is rather limited with an exception in the range from \$200/t CO_2 to \$350/t CO_2, where the abatement cost varies a little more. The electricity trains of freight sector are utilized at cost level of \$220 in EFP scenario, respectively much more than \$350 in REF scenario.

Due to a higher price of fossil fuel in the FFP scenario, the MAC curve is shifted to the right, where the abatement potential varies little. Higher fossil fuel prices induce investment into new energy vehicles like PHEVs, BEVs and FCEVs at lower carbon tax levels as they become cheaper compared to conventional fossil fuel alternatives. Meanwhile, higher prices increase the fuel cost of some public transport modes like conventional bus, ship and train, which, next to NEVs, are kinds of main abatement technologies in the transport sector. Hence the MAC curve in FFP scenario is shifted to the right.

In the range > 105 \$/t CO_2, the differences between the costs of abatement of FFP and REF scenarios become much larger, indicating that fuel price differences are not overshadowed by existing tax levels and increasing CO_2 tax levels. One reason is that fuel cost is the main component of daily fixed costs and maintenance costs for conventional transport vehicles, they consume a large quantity of fossil fuel in their lifetime. Consequently, with an increasing CO_2 tax the differences in fossil fuel production costs are difficult to be dwarfed by the tax level. It is proved that the MACs of some low carbon intensity technologies in other sectors will be robust to the fossil fuel price (Kesicki, 2013b), but it is not suitable for the high carbon intensity technologies in transport sector. Furthermore, the UK transport sector is currently characterized by fuel duties that make up approximately 75% of the price that the consumer faces at the petrol station. This means that any relative change in fossil fuel prices will be a lot less when final consumer prices are considered (Kesicki, 2013b). But the Chinese government just collect some consumption tax of fuels which is much smaller than 75%, the fossil fuel price influences the structure of MAC curve directly.

In summary, while higher fossil fuel prices lower the abatement costs for NEVs, they increase the abatement costs of some key abatement technologies, mainly like public transport modes. Fuel price differences are not overshadowed by existing tax levels and increasing CO_2 tax levels because of the particularity and importance of fuel in transport sector.

5.6 Discount rate

The discount rate is the rate at which future expected earnings within a limited period are converted into present value, it will play an important role in MAC curve. The value of discount rate will affect the results of program selection. A higher value will lead to a higher discount of the forward earnings when they are converted into the present value, so it is conducive to the generation of social benefits in the future, while the projects whose social benefits are mainly generated in the long term will be eliminated.

Social discount rate is the estimation of the time value of capital by the society. It is the standard of return rate of capital investment from the whole national economy perspective and represents the lowest rate of return on social funds. All taxes are excluded from this analysis as they are only transfers between groups in society (Kesicki, 2013). Fig. 9 shows the MAC curves for two scenarios at different levels of discount rate, HDR scenario indicates the 7% p.a. discount rate while the LDR scenario indicates the 3% p.a.

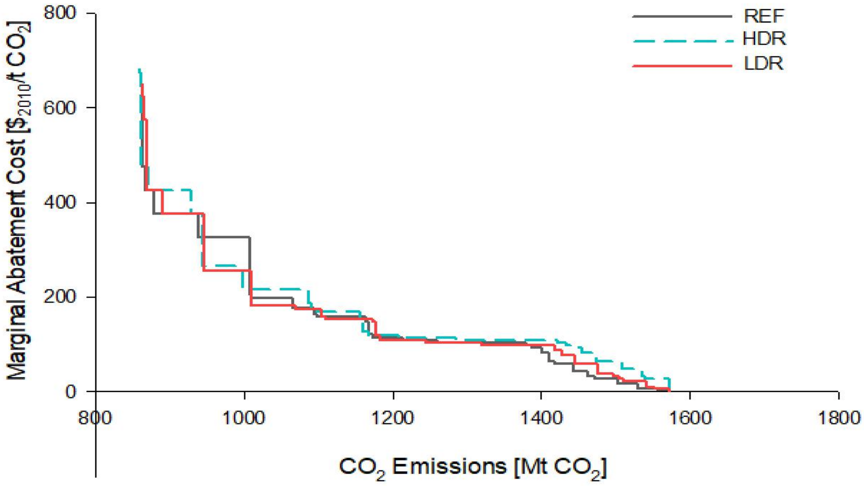

Fig. 9. MAC curve for the REF, HDR and LDR scenario in 2030

Fig. 9 shows that the MAC curve in the LDR scenario is very similar to the REF scenario, while the HDR MAC curve is significantly different in that substantially fewer emissions are abated for the same given CO_2 tax.

The LDR MAC curve is close to the REF MAC curve. The investment cost premium for abatement technologies over conventional technologies is less as the overall discount rate is lower with 3 %. Differences in fixed and maintenance costs are relatively small so they can't influence the final result. While the HDR is marginally shifted to the right from the REF scenario, it will pay more \$0.8/t CO_2 for the same level of CO_2 emissions. The investment cost premium for abatement technologies over conventional technologies is more as the overall discount rate is upper to 7 %, the abatement technologies become more expensive so the HDR MAC curve is shifted to the right.

This scenario estimates the influence of the economic factor on the pathway of transport emission mitigation. The high level of the social discount rate will affect the selection of energy-efficient projects and programs directly, so it is necessary for the Chinese government to maintain price stability and steady economic growth.

5.7 Demand level

This section shows the influence of transport demands on MAC curves. Many factors could influence the travel demands like the growth of population, the economic growth, and even consumer preference. Different predicting methods lead to different conclusions, there no consensus on the future transport demands. Therefore, all energy service demands in the TIMES model were increased by 10% in the DEM+ scenario and decreased by 10% in the DEM- scenario. Fig. 10 shows the MAC curves for both demand scenarios.

Due to a higher demand in the DEM+ scenario, the MAC curve is shifted to the right, while it is shifted to the left in the case of the DEM- scenario. The trend of carbon emissions is the same as the trend of transport demands. While a CO_2 tax of around \$65/t CO_2 is necessary to achieve a 20% emissions reduction in the REF scenario in 2030, it is around \$80/t CO_2 in the DEM+ scenario and \$60/t CO_2 in the DEM- scenario. The difference in abatement cost levels is significantly increased when lowering efforts and moving to a 50% reduction target, where the tax level is around \$105/t CO_2 in the REF scenario, \$135/t CO_2 in the DEM+ scenario and around \$125/t CO_2 in the DEM- scenario.

The differences between the MAC curves in DEM+ scenario and DEM- scenario become lager with the increased in abatement costs. At the lower end of the MAC curve, structure adjustment and optimization in internal transport sector could cover up some differences in the effects of abated carbon emissions. But along with the increasing costs, the degree of difficulty in reducing emissions is clearly differentiated. The transport demands are one kind of factors that affects the MAC curves the most.

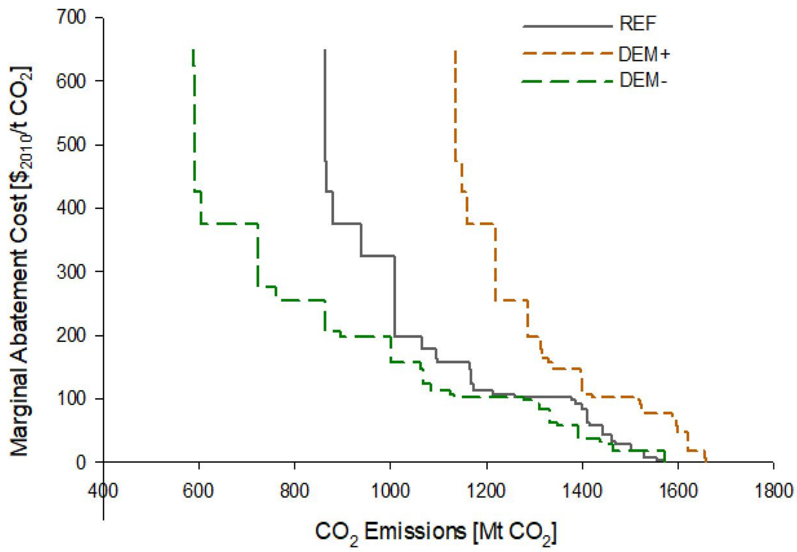

Fig. 10. MAC curve for the REF, DEM+ and DEM- scenario in 2030

6. Conclusion and policy implications

This paper presented a MAC curve for the Chinese transport sector energy system and examined the influence of different factors on the shape of an energy-system wide MAC curve. The results indicate that a system-wide CO_2 tax of around \$650/t CO_2 in 2030 would be necessary to cut emissions by 63% in 2030 compared to the no-tax model run.

According to the three sub-sectors of the system, we can see how the pressure of emission reduction of the whole transportation sector is shared among them. Intercity passenger transport sector has the cost advantage of emission reduction and accounts for almost 45.4% of all CO_2 emissions mitigation in the baseline development, and it is also the key sub-sector with the greatest potential for emission reduction which should be considered to reduce carbon emission firstly by policy makers. Although the marginal cost of emission reduction in the urban transportation sector is not so large, the potential of emission reduction is the smallest among the three sub-sectors, only 16.5% of CO_2 emissions mitigation. The freight sector has huge potential to reduce emissions but the carbon abatement costs are at a high level, from around \$115/t CO_2 upwards. Therefore, considering the economy of emission reduction, it is most effective to plan the emission reduction path of China's transportation sector in the order of intercity passenger transport sector (long distance), urban passenger transport sector (short distance) and freight transport sector.

From the perspective of technology, China's transport sector will experience the replacement of large public transportation to traditional private transportation in the early stage of emission reduction. In the later stage, as the emission reduction potential of public transportation is exhausted, new energy vehicles such as plug-in hybrid electric vehicles, battery electric vehicles and fuel cell electricity vehicles will replace traditional gasoline vehicles or diesel vehicles from \$105/t CO_2 upwards. Actually, large scale public transportation is more energy efficient and cost effective than new energy vehicles, so China's transportation departments should not only focus on new energy vehicles, but also pay attention to the application of public transportation in the process of achieving emission reduction targets.

The results show that the carbon peak policy has limited effects on the carbon potentials of MAC curves in 2030, but it has a great influence on the MAC curves after 2030. We calculated the accurate abatement cost level that can achieve carbon peaking for 2035-2050 and find that although NEVs are applied in advance under the policy shock, the increase of marginal costs of traditional techniques such as diesel buses makes the MAC curve shift to the right. It proves that the impact of carbon peaking policy on the transportation sector is too big, and in order to achieve emission reduction, it needs to pay higher costs.

Because the driver of the PHEV can choose which energy type to use, the emission reduction effect of the PHEVs is actually worse than that of the BEVs and FCEVs. However, with the support and promotion of PHEVs in China, if people can use electricity in a larger proportion than traditional energy sources, PHEV has more cost advantages and will help to reduce more carbon emissions. If it had been converted to a conventional petrol car, the more expensive BEVs and FCEVs would have replaced the PHEVs much earlier, depleting the advantage of PHEV that using alternative energy. Therefore, in addition to the cost advantages of new energy, the Chinese government should consider adopting more incentive policies to change consumption preferences of people by promoting infrastructure construction and encouraging car companies to increase battery capacity.

The sensitivity analysis has demonstrated that the MAC curve is fairly robust to variations in discount rates and electricity price. Electricity price has little impact on the marginal abatement cost curve of China's transportation sector, which proves that the current electricity price in China is already at a relatively low level, and the cost advantage of power is no longer the main factor for people to choose new energy vehicles such as plug-in hybrid electric vehicles. While the increase in the price of fossil energy reduces the cost of emission reduction of new energy vehicles, it also increases the cost of abated emission of some public transport vehicles using fossil energy, leading the overall MAC curve shift to the right and increasing the difficulty of emission reduction. Therefore, faced with the declining trend of the overall stock of fossil energy, the Chinese government should resist the pressure and try its best to stabilize the price of fossil energy in the next 30 years. The change of transport demand is positively correlated with the total carbon emission of China's transportation sector.

The results of this study were derived with the perfect foresight energy system model, which has particular strengths in considering interdependencies between urban passenger transport, intercity passenger transport and freight transport sectors. However, this study suffers from several limitations. First, some measures like buses and trucks were not sorted by vehicle size because of the lack of data, it may affect the accuracy of the TIMES modelling results. Second, the TIMES model has specific inherent disadvantage that it cannot take into account consumer preferences of each measures even if we considered about the preference between fossil fuel and electricity for PHEV drivers in this paper. In the future, we could research how consumer preferences influence the costs and potentials of reducing CO_2 emissions in a specific sector. It is significant that adding the oil refining sector and power sector to the transport sector in TIMES, completing the industrial chain to estimate the well-to-wheel CO_2 emissions of different transport technologies.

The results underline the necessity to remove market barriers in order to implement cost-effective public transport measures and NEVs in the transport sector. It illustrates that intercity passenger transport (long distance) sector is the most important sector to achieve emissions reductions. The sensitivity cases also stress the need to stabilize the price of fossil fuels and change the consumption preference of PHEV drives.

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Supporting Files

Table S1 Technology list

Sector	Technology	Fuel type	Abbreviation
Urban passenger transport (UP)	Conventional car	Gasoline	Car-UP-CON
	Battery electric car	Electricity	Car-UP-BEV
	Plug-in hybrid electric car	Gasoline; Electricity	Car-UP-PHEV
	Fuel cell electric car	Hydrogen	Car-UP-FCEV
	Conventional taxi	Gasoline	Taxi-UP-CON
	Battery electric taxi	Electricity	Taxi-UP-BEV
	Plug-in hybrid electric taxi	Gasoline; Electricity	Taxi-UP-PHEV
	Fuel cell electric taxi	Hydrogen	Taxi-UP-FCEV
	Conventional bus	Diesel	BUS-UP-CON
	Natural gas bus	Nature gas	BUS-UP-NGAS
	Battery electric bus	Electricity	BUS-UP-BEV
	Plug-in hybrid electric bus	Gasoline; Electricity	BUS-UP-PHEV
	Fuel cell electric bus	Hydrogen	BUS-UP-FCEV
	Subway-A	Electricity	Subway-A
	Subway-B	Electricity	Subway-B
Intercity passenger transport (IP)	Conventional car	Gasoline	Car-IP-CON
	Battery electric car	Electricity	Car-IP-BEV
	Plug-in hybrid electric car	Gasoline; Electricity	Car-IP-PHEV
	Fuel cell electric car	Hydrogen	Car-IP-FCEV
	Conventional bus	Diesel	BUS-IP-CON
	Natural gas bus	Nature gas	BUS-IP-NGAS
	Battery electric bus	Electricity	BUS-IP-BEV
	Plug-in hybrid electric bus	Gasoline; Electricity	BUS-PHEV
	Fuel cell electric bus	Hydrogen	BUS-FCEV
	Combustion engine train	Diesel	TRAIN-PS-DSL
	Bullet train	Electricity	TRAIN-PS-ELC
	Bunker oil ship	Bunker oil	SHIP-PS-BUKO
	Diesel ship	Diesel	SHIP-PS-DSL
	Airplane	Kerosene	APE-PS
Freight transport (FG)	Conventional truck	Diesel	TRUCK-FG-DSL
	Natural gas truck	Nature gas	TRUCK-FG-NGAS
	Battery electric truck	Electricity	TRUCK-FG-BEV
	Plug-in hybrid electric truck	Gasoline; Electricity	TRUCK-FG-PHEV
	Fuel cell electric truck	Hydrogen	TRUCK-FG-FCEV
	Combustion engine train	Diesel	TRAIN-FG-DSL
	Bullet train	Electricity	TRAIN-FG-ELC
	Bunker oil ship	Bunker oil	SHIP-FG-BUKO
	Diesel ship	Diesel	SHIP-FG-DSL
	Airplane	Kerosene	APE-FG